

To the Graduate Council:

I am submitting herewith a thesis written by Forrest McKae Utsman entitled "An Experimental Investigation On The Production Of Microfibers And The Web Defect Known As Shot For 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 Mechanical Engineering.


Mancil W. Milligan, Major Professor

We have read this thesis
and recommend its acceptance:


J. E. Hyne

Accepted for the Council:


Associate Vice Chancellor
and Dean of the Graduate School

AN EXPERIMENTAL INVESTIGATION ON THE PRODUCTION OF
MICROFIBERS AND THE WEB DEFECT KNOWN AS SHOT FOR THE MELT
BLOWING PROCESS

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Forrest McKae Utsman

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DEDICATION

This thesis is dedicated to my parents

Mr. Bill Lee Utsman

and

Mrs. Barbara Gail Sparks

who have given me invaluable educational opportunities.

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ABSTRACT

An extensive experimental investigation was performed to determine the effect that processing parameters, fiber flight dynamics, and polymer Melt Flow Rate (MFR) had on the production of microfibers and the web defect known as shot, using the melt blowing process. Both single and multi- hole die configurations, utilizing polypropylene resins ranging between 400 and 1385 MFR, were used during this investigation. Among the processing parameters that were examined were the polymer temperature, air jet temperature, and air jet exit velocity.

Using the typical melt blowing configuration, the average fiber diameter and shot intensity values decreased with increasing air jet exit velocity for the various MFR polymers investigated. Also, an increase in polymer temperature led to a decrease in average fiber diameter values and an increase in shot intensity values. As the air jet exit velocity was increased to supersonic speeds using a converging - diverging nozzle configuration, the average fiber diameter approached an asymptotic value between 1.8 and 4.5 microns. At low die stagnation pressures (subsonic flow conditions), fibers produced using a "downstream" converging - diverging nozzle were smaller than those produced using the classical melt blowing configuration.

Stop motion photography and high speed video analysis indicated that the primary mechanism causing the production of shot was not a "snapping" back phenomenon, but rather, the "touching" or colliding of molten fibers close to the die exit plane. Two types

of shot were identified; these were: (1) a shot particle within the web which resembled a film spot and showed signs of melting the adjacent fibers and (2) a shot particle within the web which showed no signs of web melting.

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LIST OF SYMBOLS AND ABBREVIATIONS

APT	analog pressure transducer
ASME	American Society of Mechanical Engineers
A_{exit}	air jet exit area
c - d	converging - diverging
DCD	die to collection distance
d_e	die orifice diameter
d_g	air gap
d_s	die setback
EDM	Electrical Discharge Machining
ghm	grams per hole per minute
gpm	grams per minute
h_m	orifice pressure drop in inches of water
$\dot{m}_{\text{air}}$	air mass flow rate
M_e	nozzle exit mach number
MFR	melt flow rate (an indirect measure of polymer viscosity)
p	static pressure at exit plane
p_o	stagnation pressure at exit plane
P_{die}	die stagnation gage pressure
R	specific gas constant

RPM	revolutions per minute
SCFM	standard cubic feet per minute
SEM	Scanning Electron Microscope
TANDEC	Tennessee Textiles and Nonwovens Development Center
T_{ao}	stagnation temperature of air jet at exit plane
T_{air}	temperature of air measured with Type K thermocouples
T_e	nozzle exit temperature
T_{poly}	polymer temperature
T_{pipe}	temperature of the air at the measuring orifice
V_{exit}	air jet exit velocity
V_e	nozzle exit velocity
V_{fj}	free jet velocity
w	air exit width

Greek Symbols

ΔP_{pitot}	pressure drop measured with pitot tube
γ	specific heat ratio
ρ_{air}	density of air
θ	air jet injection angle

CHAPTER I

INTRODUCTION

Over the past few years, the use of polymers by many manufacturing companies has been on the increase due to its unique properties of light, durable construction and ease of moldability. Polymers can be seen in all most everything we come into contact with; from the clothes we wear that contain polyester, to the car we drive with molded instrument panels and nylon seat belts. With such a wide range of products being produced using polymers, there is no doubt that polymer processes have become increasingly more complex and diverse.

The melt blowing process is one such process that has seen a steady growth in interest and research. This process is one in which raw “pelletized” polymer is melted and extruded through small orifices, contained within a die, into converging streams of heated air. As the molten polymer exits the die, the converging air streams will attenuate the polymer to fibers of small diameter. These small fibers are then collected as sheets or “webs” onto some type of moving collector. This process is used extensively to produce products such as high-performance filters, various types of medical garments, wet wipes, and many types of critical surface protection sheets and bags. A more in depth explanation of the melt blowing process is given by Malkan [1].

One of the earliest examples of the melt blowing process was in the early 1950's, when Wentz [2] undertook a project for the Naval Research Laboratory to investigate the

production of organic fibers that were less than 1 micron. By producing fibers smaller than 1 micron, the Navy felt that higher filtration efficiencies could be obtained for items such as aerosol gas masks. During his research, Wente discovered that, while using the melt blowing process, an increase in polymer throughput increased the fiber diameters and that various polymer characteristics contributed to the production of small fibers. These characteristics were listed as melting point, viscosity-temperature characteristics, and surface tension that incorporated intermolecular forces.

Since Wente's research, much work has been done concerning the production of small fibers to improve filter efficiencies. Milligan and Haynes [3] showed that the flapping motion of a cylindrical fiber in the axial flow field of a free jet, enhanced the fiber's attenuating force or drawing force (drag). Uyttendaele and Shambaugh [4] reasoned that an increase in drawing filament force was the primary explanation for high prediction rates of their general equation model of the melt blowing process. Examining die geometry, Kayser and Shambaugh [5] showed that by using orifice diameters smaller than the conventional size, smaller fibers were consistently produced. This was also the conclusion found by Wadsworth and Muschelewicz [6] after their investigation with various polypropylene resins or polymers. Malkan [1] investigated the effects that air temperature, polymer throughput, die orifice diameter, and polymer temperature had on fiber diameter. The conclusion of his research, like that of Wente, showed that polymer throughput plays a major role in the production of small fibers. Lee and Wadsworth [7] found that an increase in processing temperature resulted in webs of smaller average fiber diameters,

thus causing webs to have greater filtration efficiencies. Straeffer and Goswami [8] reported that by increasing the velocity of the air stream, smaller and more uniform fibers were produced. This was also observed by Wadsworth and Muschelewicz [6] who saw a significant reduction in mean fiber diameter as the air velocity increased. Milligan, Lu, Buntin, and Wadsworth [9] found that by utilizing a stream of unheated crossflow air, there was a large reduction in fiber diameter for all values of polymer throughputs resulting in finer fibers and more uniform webs.

Although a considerable amount of research has focused on the production of small fibers in order to improve filtration efficiencies, little has been done on the more complex problem of "shot" production. This phenomenon has been shown to affect the web filtration efficiency in a detrimental way when present. The observation and production of shot can be traced all the way back to Wente's [2] work with the Naval Research Laboratory. During this work, Wente described a situation in which filter efficiencies dropped due to the undesirable presence of many shot particles. He described shot as being caused by the breaking of the molten polymer fiber, thus causing a globule of solid material larger in diameter than the fiber itself to form at the ends of the broken fiber. He surmised that an abundance of this shot would adversely affect the filtration performance. Therefore, Wente was one of the earliest known melt blown process users to observe this undesirable phenomenon.

Since then, other investigators have also described the shot phenomenon being caused by the breaking or splitting of fibers. In 1973, Buntin and Lohkamp [10] reported

that during the normal operation of the melt blowing process, the converging high-speed air streams caused the extruded molten fibers to be broken into lengths on the order of a few inches. Once broken, the ends of these fibers would elastically “snap back”, thus creating a globule or shot particle. Shambaugh [11] later expanded on this idea in order to determine the conditions where shot was not produced. He concluded that there were three distinct regions for the melt blowing process. These regions were:

1. Low gas velocity region, continuous fibers with final diameters typically $\geq 10\mu\text{m}$.
2. Unstable region, the filaments break up into fiber segments and undesirable lumps or shot are formed. These shot particles add a coarseness to the final product.
3. Increased gas velocity region. Shot is still present but is attenuated to very small diameters by the high-velocity air. Fiber diameters are typically from $10\mu\text{m}$ down to $0.1\mu\text{m}$.

In order to find what process characteristics affected these regions the most, Shambaugh [11] performed a dimensional analysis on the melt blowing process. This analysis showed that, of the more than a dozen variables involved, the gas Reynolds number, polymer Reynolds number, fiber diameter, and the viscosity ratio of the polymer to the air were the dominant variables affecting these three regions. In 1990, Malkan [1] reported that shot

can be attributed to periodic melt fracture or melt instability. Based on this conclusion, he lists some of the causes and solutions of shot; e.g., blocked die orifice holes. Like Shambaugh's [11] three regions, Malkan also demonstrated a "perceived process condition window" describing the conditions at which the melt blown process could be operated without producing the undesirable shot particles.

All of the aforementioned studies were based on the idea that shot was primarily caused by the breaking or splitting of fibers. However, in 1991, Milligan and Haynes [12] used stop motion photography of a single fiber in "flight" to show that fibers were actually continuous filaments that varied in diameter along their lengths. This conclusion undoubtedly changed the fundamental idea behind the causes of shot and became the underlying theme behind the current research.

Objectives

The following is a list of the major objectives that were addressed during this research:

- examine the effect of various polymer MFRs (Melt Flow Rate) on the production of shot and average fiber diameter.
- examine the effect that changes in polymer temperature have on the production of shot and average fiber diameter.

- examine the plane motion of multi- and single-hole die extruded fibers in "flight" using stop motion photography and high speed video.
- examine the centerline air velocity profile for a standard Exxon multi-hole converging nozzle configuration.
- examine the effect that various nozzle configurations resulting in supersonic flow of the air stream have on the average fiber diameter for multi- and single-hole die configurations.

CHAPTER II

EXPERIMENTAL SETUP AND PROCEDURES

This chapter describes the typical experimental setup and procedures used to obtain web samples for this investigation. The chapter is presented in three sections. These sections are Meltblowing Facility, Experimental Procedures, and Data Reduction. The first section gives a brief description of the equipment that makes up the Meltblowing Facility. The second section describes the procedures that were used to collect web samples and other pertinent data. Having collected web samples, the last section gives a short explanation of how these samples were examined for average fiber diameter and shot characteristics. Since this project was part of the research effort supported by the Exxon Corporation over the past few years, these procedures and equipment setup descriptions are very similar to those outlined by Haynes [13] and Spencer [14]. What few differences there are can be attributed to the use of a multi-hole die and a moving round collector. Finally, it should be noted that only polypropylene supplied by the Exxon Corporation was used during this investigation.

Meltblowing Facility

The meltblowing facility is located on the Mezzanine floor of the Mechanical and Aerospace Engineering Building at the University of Tennessee, Knoxville. As described by Spencer [14], this facility can be thought of as being composed of three major pieces of equipment. These pieces are: the screw extruder, the die test section, and the air supply system. A simplified drawing of the entire meltblowing facility is shown in Figure 2.1.

Single Screw Extruder

The primary function of the extruder is to supply a constant flow of molten polymer to the die test section. The extruder used in this investigation was an instrumented Killion Single Screw Extruder. As can be seen in Figure 2.2, the melting of the polymer was accomplished by heating the polymer in five consecutive stages using band heaters. A motor driven single screw was used to establish the desired polymer flow rate (throughput) going into the die test section. As mentioned by Spencer [14], in order to ensure constant polymer flow rate, a Dynisco pressure sensor located between zones 4 and 5 was used to monitor the pressure being exerted by the polymer on the tube walls. To replenish the polymer that was extruded through the die test section, raw polymer was fed into the hopper at regular intervals. The extruder's zone heaters and motor speed was controlled by the control panel shown in Figure 2.2.

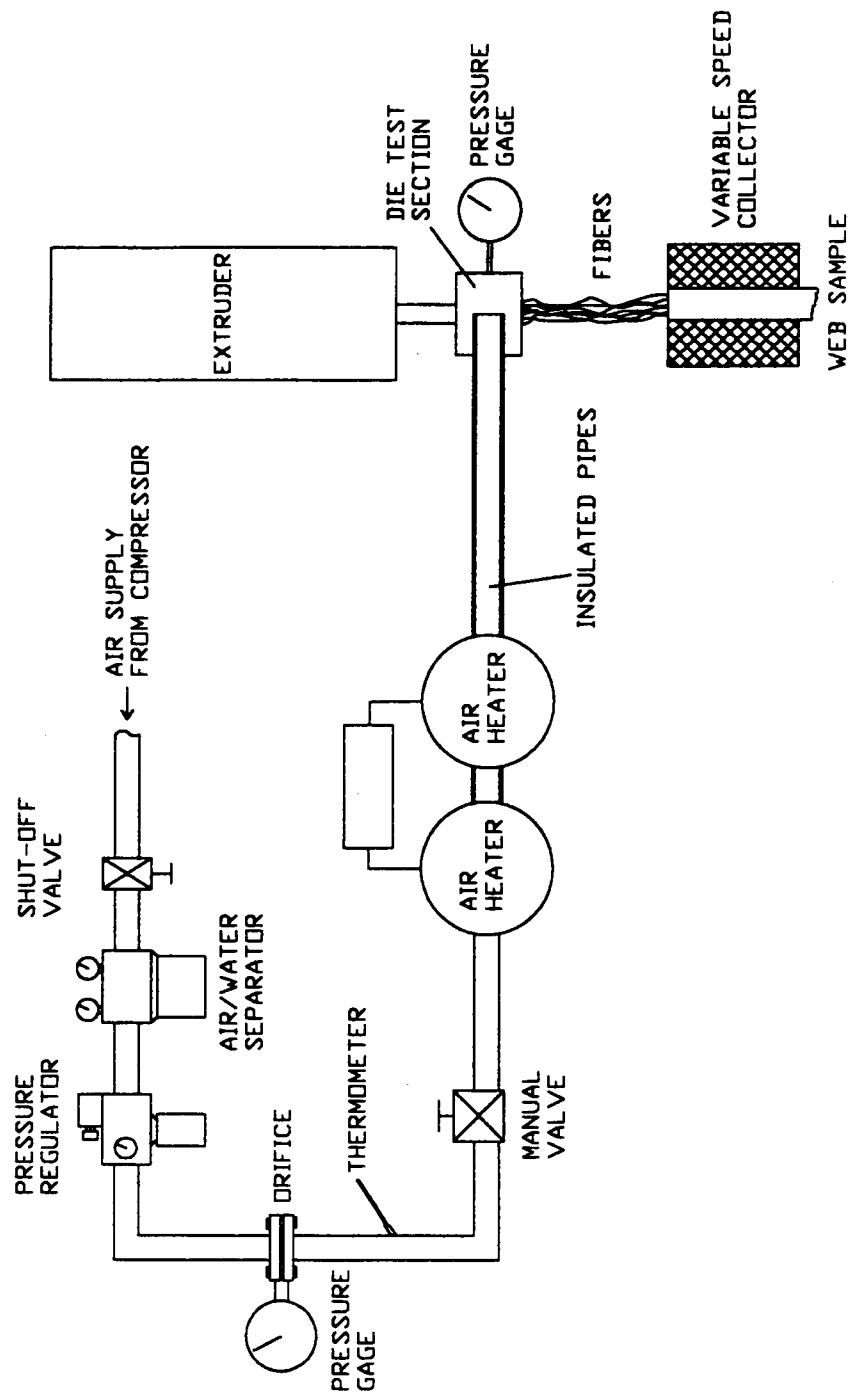


Figure 2.1: Drawing of the multi-hole melt blowing facility at the University of Tennessee Knoxville.

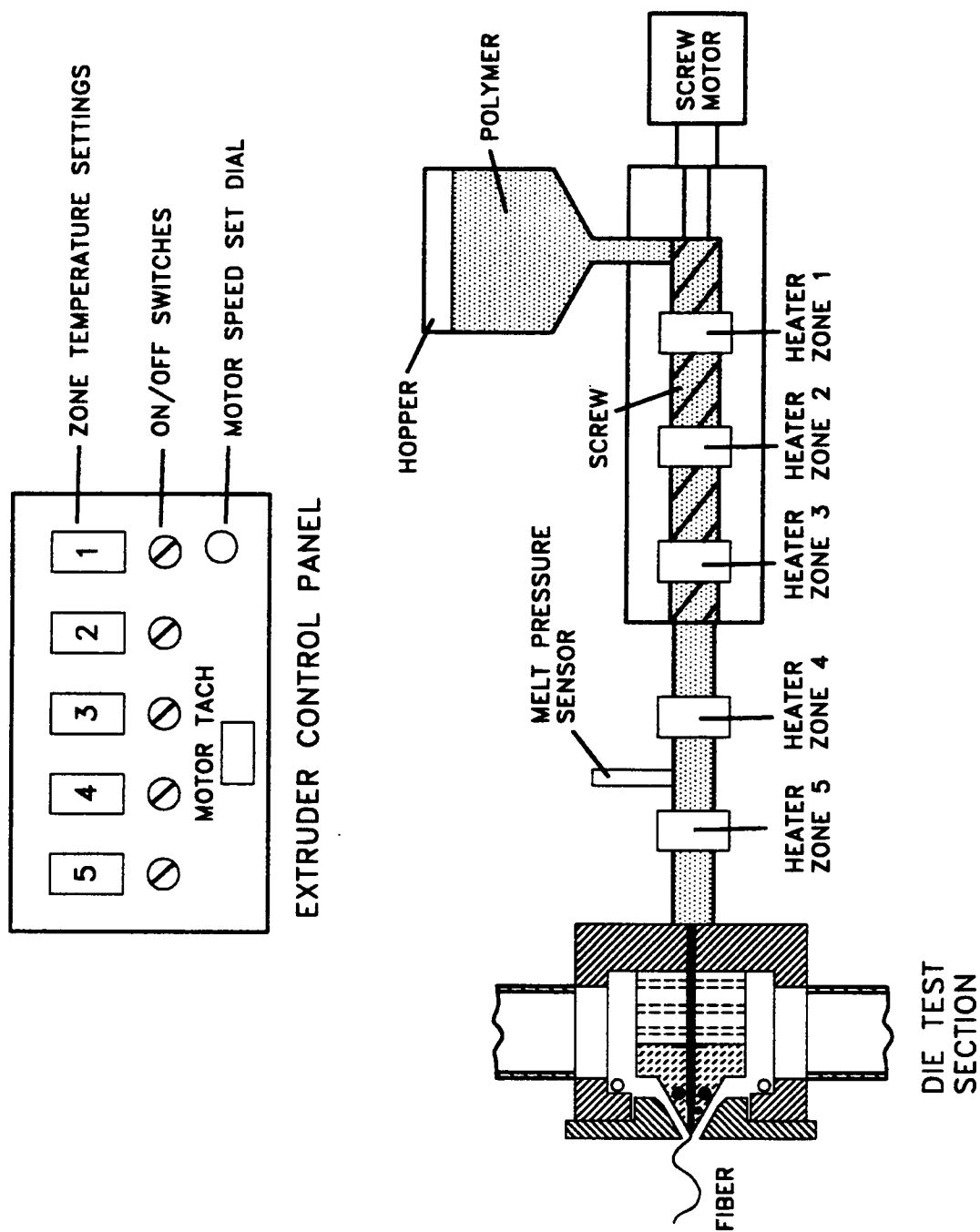


Figure 2.2: Cross-sectional view of the single screw extruder and die test section.

Die Test Section

Figure 2.3 shows a cross-sectional view of the die test section that was used during this research. The die test section is composed of a spacer block, 30 degree nosepiece, two cartridge heaters, air thermocouples, polymer thermocouple, pressure gauge, and upper and lower adjustable face plates. A detailed description of these components is given by Spencer [14], but for convenience, a brief description will be stated here. Polymer from the extruder flows through the spacer block, through the screen pack, and into the 30 degree nosepiece where it then exits through small die orifice holes into converging streams of heated air. The spacer block was used as an adjustment piece for the nosepiece. This block has a series of through holes that allow equalization and mixing of the air between the upper and lower regions of the test section. The screen pack was strictly used as a deterrent against any form of foreign particles that might clog one of the die orifice holes. The nosepiece contained two cartridge heaters rated at 280 watts each to establish the desired polymer temperature at the die tip, a Type K thermocouple to measure the polymer temperature, and 30 die orifice holes (per inch) whose diameters were 356 microns each. To create the converging air streams, adjustable face plates were mounted near the end of the nosepiece. These plates could be adjusted either vertically or horizontally depending on the desired test configuration. A pressure gage and a Type K thermocouple were used to measure the stagnation pressure and temperature of the heated air before leaving the die test section.

In order to determine the relationship between die setback (ds), air gap (dg), and

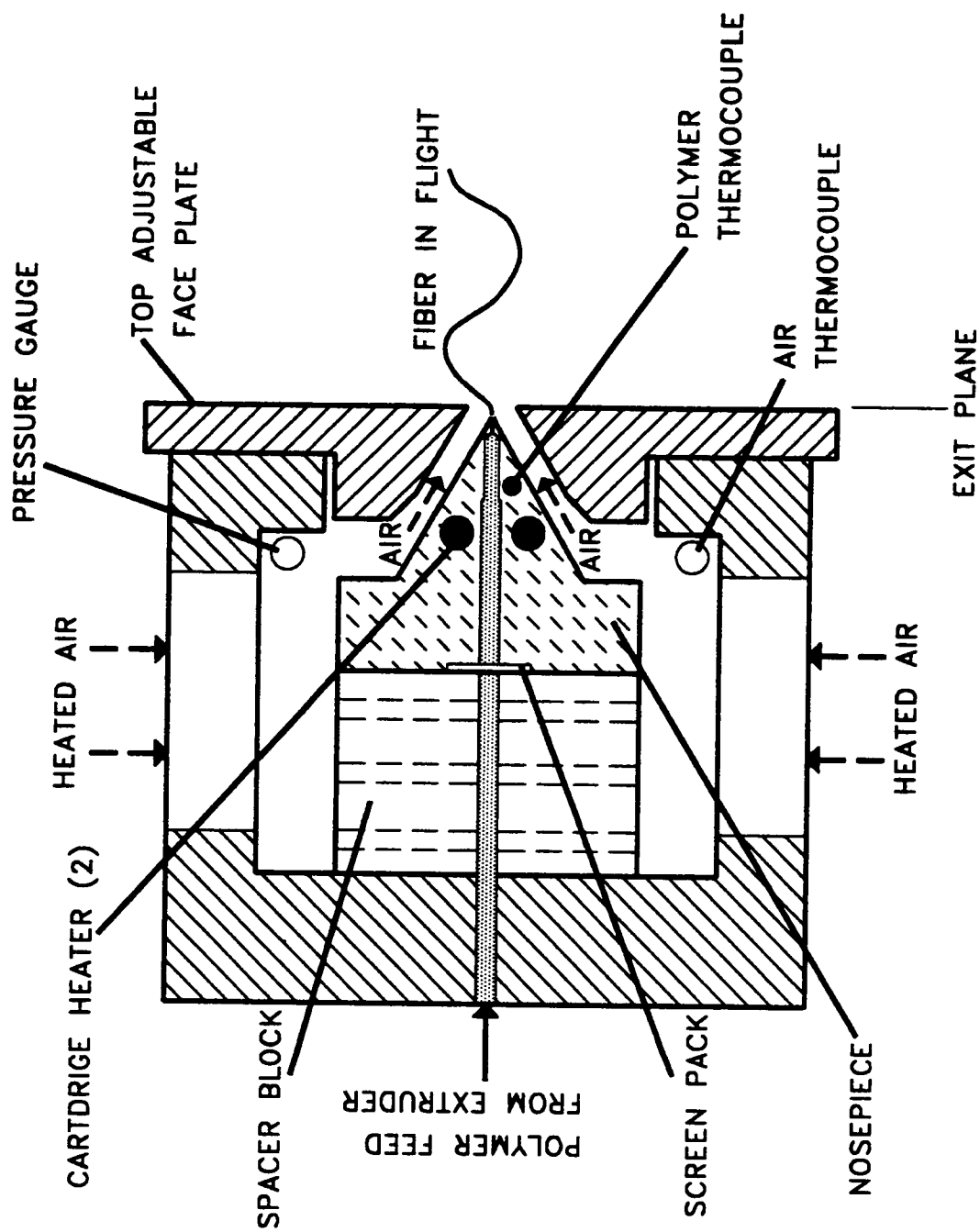


Figure 2.3: Cross-sectional view of the die test section with converging nozzle face plates.

air exit width (w), for the typical melt blowing configuration, a simple geometric analysis was used. Figure 2.4 shows the geometric layout of the nosepiece and the two adjustable face plates. From this figure and simple geometry, an equation for the air exit width can be derived as a function of the die setback, air gap, nosepiece angle (θ), and die orifice diameter (d_e). This equation was found to be:

$$w = 2 \left[\frac{dg}{\cos \theta} - ds(\tan \theta) \right] + d_e \quad 2.1$$

Where the values of 30 degrees and 0.396 millimeters (0.0156 inch) were used throughout this investigation for θ and d_e , respectively. The typical values of ds , dg , and w that were used for this investigation were 2, 2, and 2.72 millimeters (0.079, 0.079, 0.107 inches), respectively.

Finally, it should be mentioned that, due to the high temperatures experienced while using the melt blowing process, all of the die test section components were constructed of cold rolled steel.

Air Supply System

The air supply system is depicted in Figure 2.1. This system supplied a continuous amount of compressed air to the die test section for extended periods of time (typically 5 hours). This air was supplied by a compressor located within the building. This compressor was capable of supplying 250 standard cubic feet per minute (SCFM) of

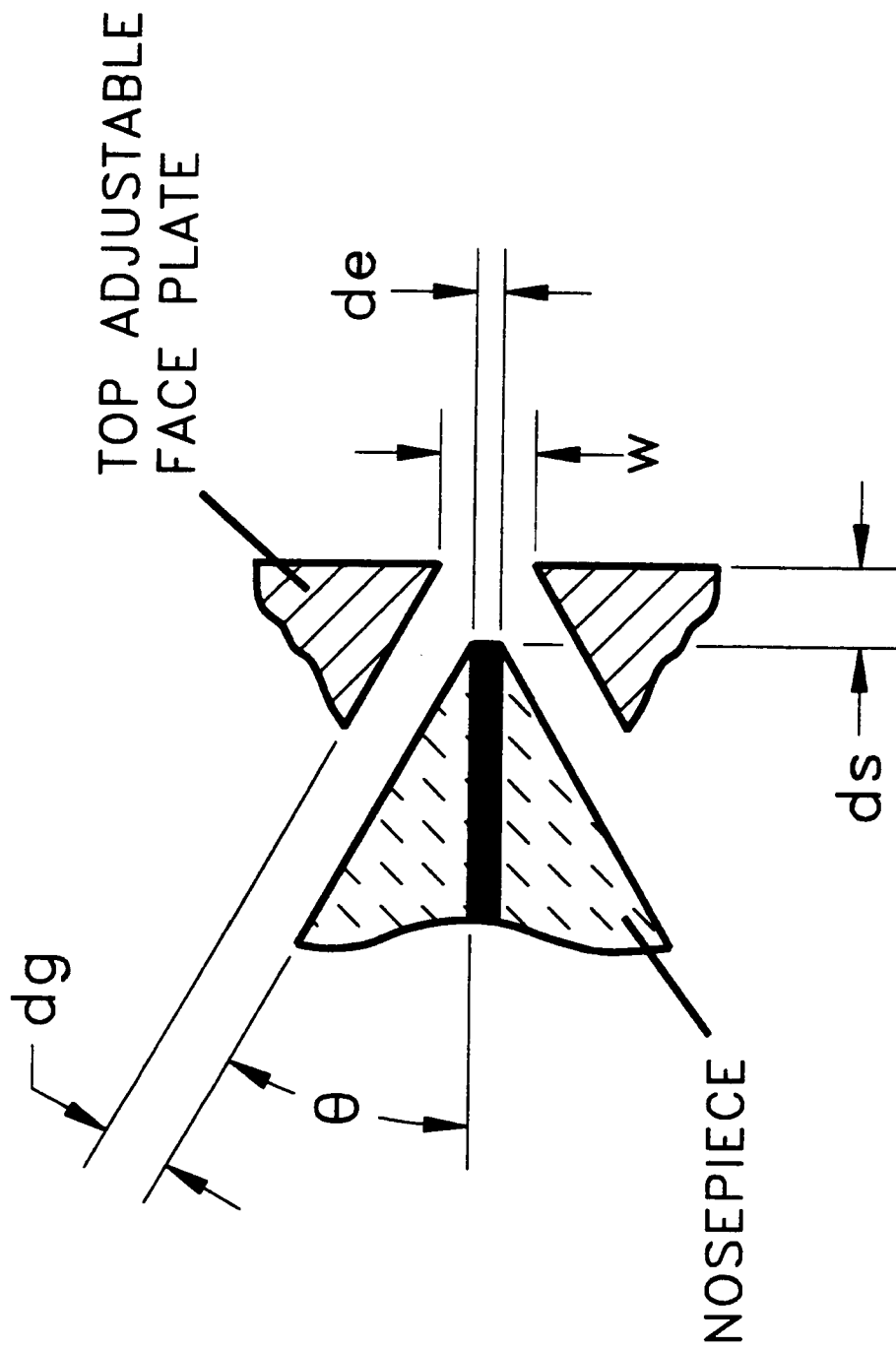


Figure 2.4: Geometric layout of the nosepiece and adjustable face plates showing die setback, air gap, die orifice diameter, and air exit width.

compressed air at a pressure of 110 psig. After leaving the compressor, the air passed through a 2 inch steel pipe, into an air-water separator, then into a pressure regulator which dropped the pressure from 110 psig to 50 psig. From the pressure regulator, the air would then flow through a measuring orifice. The pressure drop across the measuring orifice was measured with a pressure gage calibrated in inches of water. This orifice allowed the mass flow rate of the air to be determined using the American Society of Mechanical Engineers (ASME) Flow Measurement Code [15]. After passing the orifice, the air then flowed past a Fisher thermometer, which was used to measure the air temperature in the pipe, and into a manual (throttling) valve. This manual valve was used to control the amount of air flowing into the die test section; i.e., to change or set the air exit velocity at the die. Next, the air would enter two Accutherm air heaters. These air heaters were arranged in series and controlled using a thermocouple located at the air heater exit and a control panel attached to the side of both heaters. In order to obtain the prescribed test air temperature at the die test section, the air heaters were set according to a known calibration curve determined by Spencer [14]. Upon leaving the air heaters, the heated air would then enter a 2 inch insulated steel pipe that branched off into two 2 inch insulated steel pipes. These pipes were connected to the upper and lower regions of the die test section. Once in the die test section, the air would then flow out through the converging nozzle defined by the adjustable face plates. A drawing of the front of the die test section showing the location of the heated air supply pipes is shown in Figure 2.5.

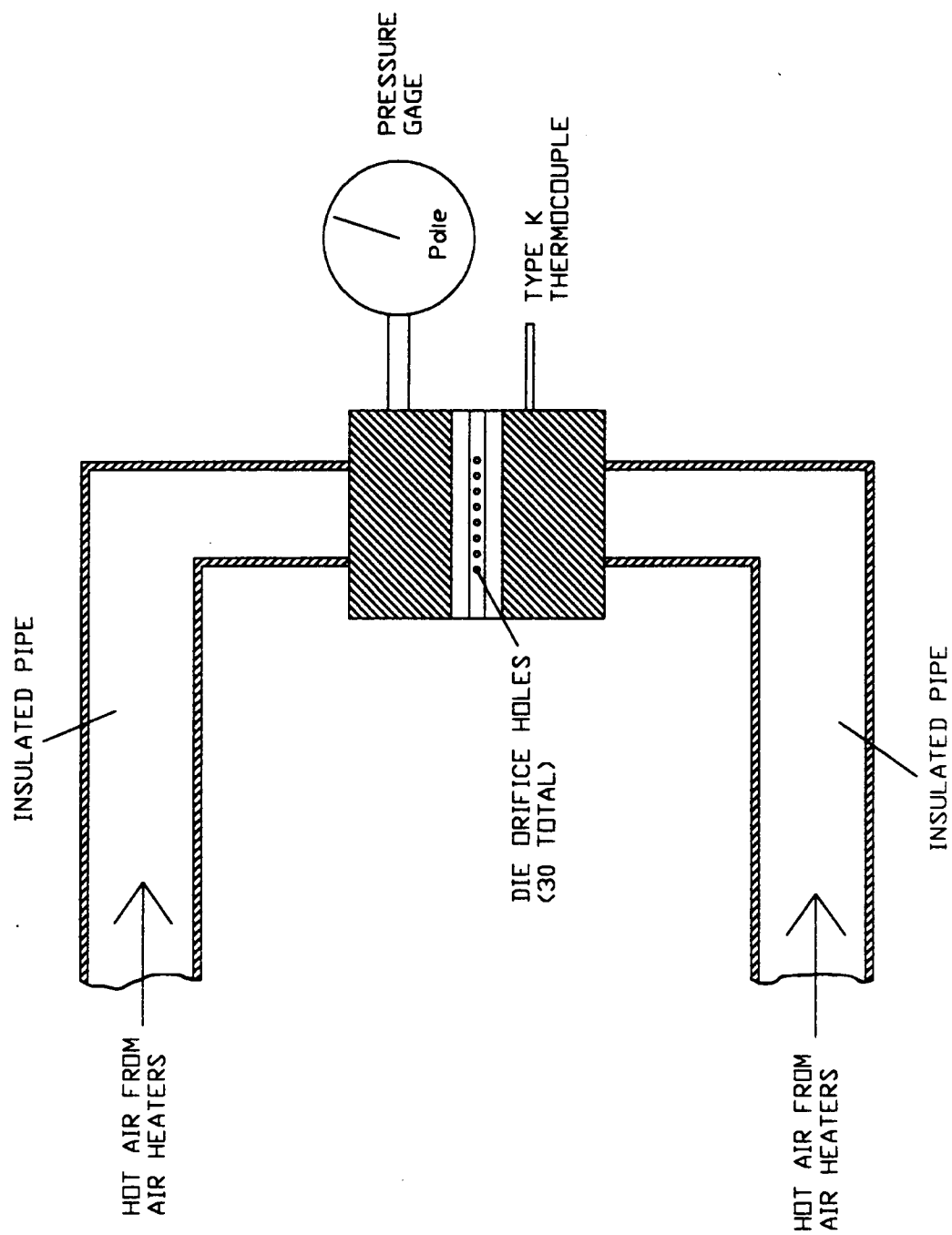


Figure 2.5: Front view of the die test section showing the heated air supply lines.

Experimental Procedures

As was mentioned previously, the procedures used to perform a typical experimental run were very similar to those used by Haynes [13] and Spencer [14]. Again, as was done for the die test section, the experimental procedures will be briefly mentioned here for completeness. Before collecting a sample, it was first necessary to establish the steady-state run conditions that were needed for the given test. This was done by turning on the air supply, using the manual throttling valve, to a “home” position of $h_m = 2$ inches of water on the orifice pressure gage. Then the air heaters and all five zone heaters of the extruder were set to the test’s pre-specified temperature. Once all the heaters had reached their set temperatures, the screw motor was turned on and adjusted to obtain the proper polymer flow rate (throughput). Having obtained the required polymer throughput, the throttling valve was then either opened up or closed down in order to increase or decrease the amount of air flow to the die test section; thus, causing an increase or decrease in the desired air velocity at the die exit. Once the air velocity was set, and enough time was allowed for the system to reach steady state conditions at the new air velocity, a web sample was collected.

Collection of Web Samples

The collection of samples for the multi-hole die differs from the way Spencer [14] collected samples for the single-hole die. Instead of collecting fiber samples by using a flat

plate swiped in front of the exiting polymer flow stream, the fiber samples were collected using a variable speed cylindrical collector placed a certain distance from the die exit plane. This distance is called the die to collection distance or DCD (typically 16 inches). By using a variable speed collector, the thickness of the web could be controlled. This collection process is illustrated in Figure 2.6.

Recording of Temperatures, Pressures, and Screw Speed

Each time a web sample was collected, it was imperative to record the test parameters. Therefore, for each sample, the polymer and air temperatures measured by the Type K thermocouples, the air temperature in the research lab, the stagnation air pressure measured by the die test section pressure gage (P_{die}), the h_m across the measuring orifice, the melt pressure, and the screw RPM were recorded onto a data collection sheet.

Data Reduction

The reduction of the data primarily consisted of determining the average fiber diameter and shot characteristics for each web sample collected. This section describes the procedures used to obtain these web characteristics.

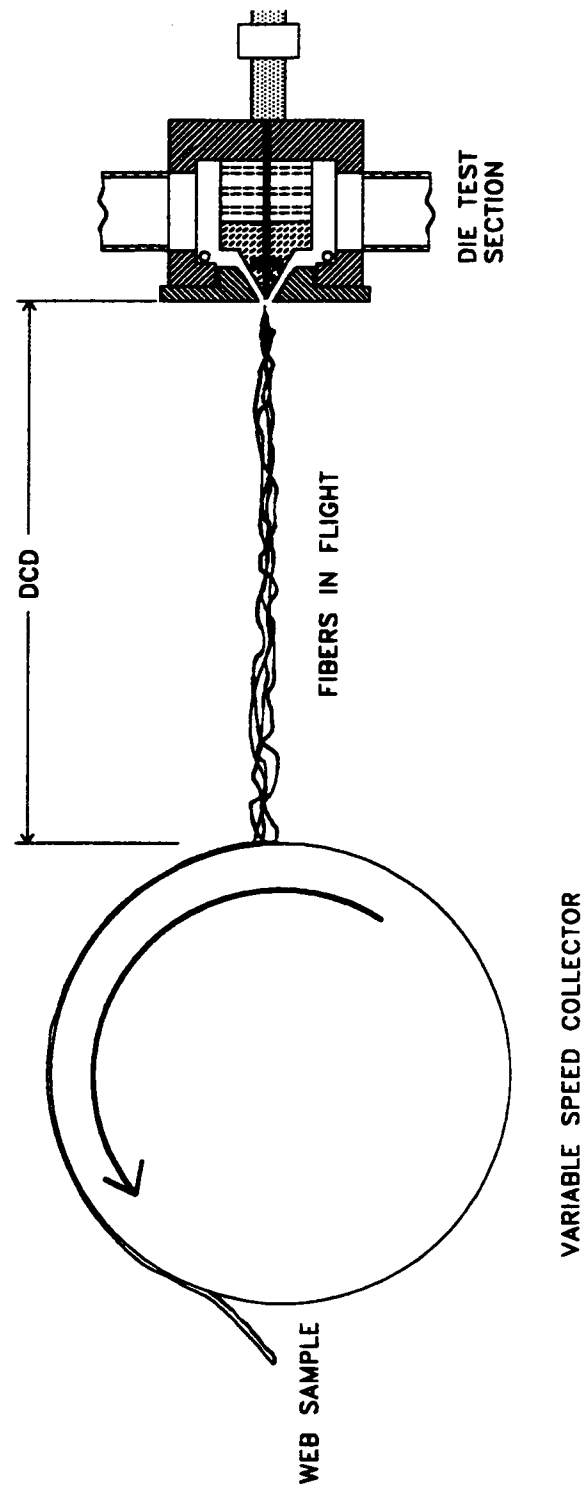


Figure 2.6: Collection process for the multi-hole die web samples.

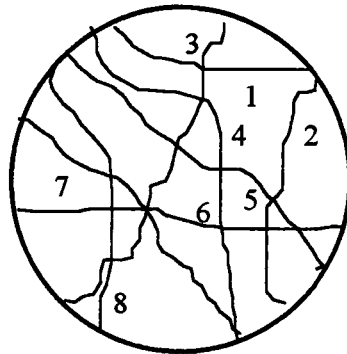
Fiber Diameters

The procedure used to determine the average fiber diameters of the web samples is identical to the procedure Haynes [13] and Spencer [14] used for their experiments. This procedure consisted of using an Olympus optical microscope containing a scaled eyepiece and a 400X magnification to take several measurements of individual fibers within a 1 inch square segment of each web sample. These measurements were taken at three arbitrary locations, where approximately, 9 to 15 individual fiber diameters were measured and recorded as diameter counts onto a data sheet. An example of this sheet is shown in Figure 2.7. Having recorded these counts, they were then put into a computer code written by Haynes [13]. Haynes's code takes these counts and performs a statistical analysis resulting in the output of average fiber diameter, standard deviation, and diameter count histogram data. The uncertainty of fiber diameter measurements using this technique was stated by Haynes [13] to be a conservative ± 1.25 microns. Due to the amount of data that was collected, three undergraduate students helped in performing the fiber diameter measurements for this investigation. With so many individuals performing measurements, the affect of human subjectivity is important. During Haynes [13] investigation, he also had several individuals helping in the reduction of data. He found that, while examining a single sample having an average fiber diameter of 8.42 microns, there was a maximum difference of only 0.4 microns between the measurements of the individuals, which is less than the ± 1.25 micron uncertainty of the fiber diameter measurement scheme. Therefore Haynes [13] concluded that the human subjectivity could be considered negligible.

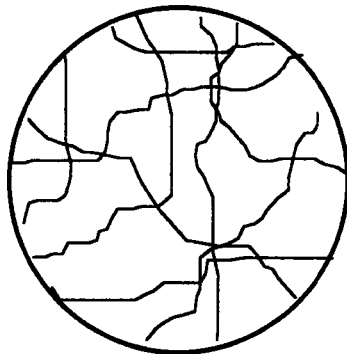
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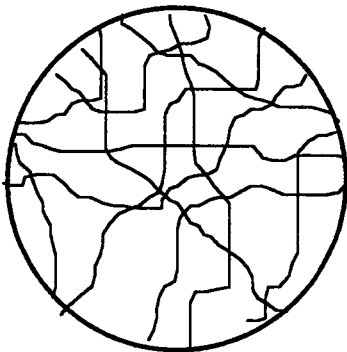
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 2: 1
 3: 5
 4: 2.5
 5: 4
 6: 8
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 8: 1.5
 9: 3
 10: 2
 11: 1.5

Figure 2.7: Example of fiber diameter measurement using an optical microscope.

In addition to the use of an optical microscope to obtain fiber diameter measurements, some of the samples collected were examined using a SEM (Scanning Electron Microscope). This microscope allowed fibers whose diameters were less than 2 microns to be seen more clearly. To obtain fiber diameter measurements, a one inch square sample was cut from the main web sample and placed within the SEM chamber. Then, using magnifications of either 400X or 600X, two approximately 0.03 micrometer squared areas were randomly selected and photographed. For each photograph, a line was then drawn diagonally from corner to corner. The fibers crossing this line were then measured and recorded. It should be noted that, any fiber crossing the line twice or more was only measured and recorded once.

Shot Rating

Shot was defined in the introduction as a globule of polymer having a diameter much larger than the average fiber diameter. In order to come up with a way to characterize shot, a technique called, "shot rating" was developed by the University of Tennessee Textiles and Nonwovens Development Center (TANDEC). This technique gave the melt blowing industry a way to quantify shot on a scale of 1 to 5, with 5 having the most shot present. Before a shot rating can be acquired for a given web sample, the sample must first be approximately 1 ounce per square yard in composition. This sample is then laid out on a light table and compared to a baseline group of webs that have already been given a rating of 1 to 5. Although this technique is widely used, it has many

limitations, the most apparent being that, the results are strongly influenced by the person performing the comparison.

Shot Intensity

A collaboration was done with Wallen [16] to develop another technique for classifying shot called, "shot intensity." It was desired to develop a technique which would be less subjective than the shot rating scheme. The following equation defines how shot intensity is calculated:

$$\text{shot intensity} = \frac{(\# \text{ of shot particles counted})}{\left(\frac{\text{weight of the sample in mg}}{\text{area of the sample in cm}^2} \right)} \quad 2.2$$

To determine the shot intensity value of a web sample, a 1 inch square piece of the web was cut out, weighed, and placed under a Nikon optical microscope using polarized light with a 40X magnification. The sample was then scanned from left to right until the complete 1 inch area was covered. As the sample was scanned, the number of shot particles was counted and recorded. This data was then entered into Equation 2.2.

Nozzle Exit Air Velocity

By using the measuring orifice and the ASME Flow Measurement Code [15] previously described, the mass flow rate of the air could be determined. A simplified version of the mass flow rate equation is given by Spencer [14]. Assuming a constant atmospheric pressure of 14.7 psia, this equation is:

$$m_{air} = 2.45 * 10^4 \sqrt{\frac{h_m}{1.8 T_{pipe} + 492}} \quad 2.3$$

where: m_{air} air flow rate in grams per minute
 h_m orifice pressure drop in inches of water
 T_{pipe} pipe temperature in degrees Celsius

By applying the principle of conservation of mass [17], the mass flow measured at the orifice must equal the mass flow at the die test section exit. Therefore, using this principle, ideal gas relations, and assuming an isentropic process; the equation for the nozzle exit air velocity is given by:

$$V_{exit} = \frac{m_{air} R T_{ao}}{A_{exit} p} \left[\frac{p}{p_o} \right]^{\frac{\gamma-1}{\gamma}} \quad 2.4$$

or,

$$V_{\text{exit}} = \frac{m_{\text{air}} R T_{\text{ao}}}{A_{\text{exit}} (0.5283 * p_o)} [0.5283]^{\frac{\gamma-1}{\gamma}} \quad 2.5$$

Where Equation 2.4 is for a nonchoked nozzle and Equation 2.5 is for a choked nozzle situation. A detailed derivation of these two equations was done by Spencer [14].

CHAPTER III

EXPERIMENTAL INVESTIGATION OF POLYMER CHARACTERISTICS

In Chapter II, it was stated that polypropylene was used as the investigating polymer throughout this research. This polymer has become one of the most widely used polymers within the melt blowing industry. Its popularity has spurred many companies to develop their own "special" blends; i.e., variations of the polypropylene molecular make-up. These variations can primarily be attributed to changes in molecular weight, changes in MFR (Melt Flow Rate), and the addition of certain "additives" to the polymer's raw batch. Typically, the web characteristics of these blends can be highly dependent upon the polymer temperature that is used during the extrusion process. This chapter details the various polymers (blends) that were examined in this study to determine what effect, if any, variations in MFR and polymer temperature would have on average fiber diameter and shot values. The chapter has two main sections. These sections are: (1) Experimental Investigation of Various Polymers and (2) Experimental Investigation of Changes in Polymer Temperatures. Since the term MFR will be used extensively throughout this report, it should be noted that MFR is identical to the more commonly known Melt Index Value (amount of molten polymer in grams that flows out a melt indexer in 10 minutes).

Experimental Investigation of Various Polymers

This portion of the chapter has five topical sections. These sections are 400 MFR, 800 MFR, 1000 MFR, General Test Procedures, and Repeatability. Sections one through three describe the different MFR polymers that were examined. Section four explains the procedures used to obtain web samples and data reduction. The last section defines the polymers that were employed for a repeatability study.

400 MFR

Since the main goal of this research was to help current melt blowing industries, it was decided that the polymers used should consist of typical industry polymers. The first group of these typical polymers ranges from 400 to 475 MFR. These polymers were as follows:

1. 400-A - Broad molecular weight distribution (400 MFR).
2. 400-B - Narrow molecular weight distribution (475 MFR).
3. 400-C - Very narrow molecular weight distribution (400 MFR).

These polymers, along with their defining characteristics, were supplied by the Exxon Corporation, in Baytown, Texas.

800 MFR

The next group looked at ranged from 780 to 800 MFR. The following is a list of the polymers that were examined.

1. 800-A - Very narrow molecular weight distribution with additives (780 MFR).
2. 800-B - Medium molecular weight distribution (800 MFR).
3. 800-C - Medium molecular weight distribution that has been twin screwed (800 MFR).
4. 800-D - Medium molecular weight distribution, twin screwed, with 1000 PPM nucleating agent added (800 MFR).
5. 800-E - Medium molecular weight distribution, twin screwed, with 2000 PPM nucleating agent added (800 MFR).
6. 800-F - Broad molecular weight distribution (800 MFR).

Again, these polymers and characteristics were supplied by the Exxon Corporation.

1000 MFR

The final group studied consisted of polymers ranging from 1000 to 1385 MFR.

These were as follows:

1. 1000-A - Medium molecular weight distribution (1000 MFR).
2. 1000-B - Medium molecular weight distribution (1000 MFR).

3. 1000-C - Medium molecular weight distribution (1385 MFR).
4. 1000-D - Very Narrow molecular weight distribution with additives (1115 MFR).

Since all the polymers used in this study were supplied by the Exxon Corporation, some of the resins either contained special "additives" or had some other special characteristic that was deemed proprietary by the company; thus, restricting any detailed description of the polymer to be given within this chapter.

General Test Procedures

The procedures used to obtain web samples were the same for each of the three polymer MFR ranges. Initially it was decided that all samples would be collected at air velocities of 143, 220, and 327 meters/second at a polymer throughput of 0.8 and 1.2 grams/minute per hole. This allowed a comparison of the varying polymers to be made at similar conditions. For each situation of air velocity and polymer throughput, a sample was collected in accordance with the description given in Chapter II. Having collected the samples, the procedures outlined in Chapter II were then employed to determine the average fiber diameters, shot intensity, and shot rating values. Finally it should be mentioned that whenever a polymer was changed over to a new one, the extruder was purged by running at high polymer throughputs for approximately 2 hours. In the past it was found that 2 hours was the time it took to completely purge 6 ounces of red

polypropylene resin from the system.

Repeatability

With such a broad range (400 to 1385 MFR) of polypropylene resins being used and the fact that during the change over of a polymer, some residue of the old polymer could possibly still be present after the 2 hour purge time, it was decided that a repeatability study should be made for some of the various MFR cases. The main purpose of this study was to determine if similar results for the average fiber diameter and shot values could be obtained for a given polymer, at the same conditions, on a different day. The polymers that were examined are listed as follows:

1. For the 400 MFRs: 400-A and 400-B.
2. For the 800 MFRs: 800-B.
3. For the 1000 MFRs: 1000-A and 1000-B.

Experimental Investigation of Changes in Polymer Temperature

The affect that changes in polymer temperature have on web physical characteristics, specifically average fiber diameter and the presence of shot, have been mentioned by Spencer [14] and Malkan [1]. In his research, Spencer [14] discussed how average fiber diameters changed with changes in polymer temperature for a single hole die

configuration. Malkan [1] on the other hand, briefly mentions that one possible cause of shot could be operating at too low a polymer temperature. Therefore, this investigation was undertaken in order to determine if results similar to those obtained by Spencer [14] could be achieved using a multi-hole die configuration. Also, shot intensity values were calculated to examine the influence that the temperature changes had on the amount of shot present within the web. This section summarily describes the collection and data reduction of the web samples.

Shot Intensity

Only one polymer (1000-C from Chapter III) was employed for this investigation. Polymer throughput and air temperature were held constant at 0.8 grams/minute per hole and 400 degrees Fahrenheit, respectively. The polymer temperature was varied between 364 and 450 degrees Fahrenheit. After collecting samples, shot intensity values were then calculated using the procedures described in Chapter II.

Fiber Diameter

Average fiber diameters were determined using an Olympus optical microscope with a scaled eyepiece as detailed in Chapter II.

CHAPTER IV

EXPERIMENTAL INVESTIGATION OF FIBER DYNAMICS AND AIR FLOWFIELD CHARACTERISTICS

As mentioned earlier, Milligan and Haynes [12] discovered through the use of stop motion photography of a single fiber in “flight,” that the extruded molten fiber was actually a continuous filament with a varying cross-section along its length. Based on this, the classical idea that the extruded filaments break into small fragments causing shot to form at the broken ends appears not to be the case for typical industry operating conditions. Therefore, a new way of thinking concerning the production of shot was needed. However, before a new idea could be developed, it was desired to try and understand two of the most important physical characteristics of the melt blown process. These characteristics are: (1) how the molten filaments behave within a single plane as they exit the extruder and (2) how the air flowfield changed in velocity with distance from the die exit plane. These characteristics make up the two main sections of this chapter. These sections are Experimental Investigation of Fiber Motion in a Single Plane and Experimental Investigation of a Converging Nozzle Flowfield.

Experimental Investigation of Fiber Motion in a Single Plane

To gain an understanding of how the fibers interacted with each other upon leaving the die nosepiece, stop motion photography and high speed video analysis of the fibers in flight for the multi- and single hole dies was performed. This portion of the chapter gives a description of the two photography techniques used. This description is detailed in the following two sections called Multi-Hole Stop Motion Photography and Single Fiber Plane Motion and Frequency.

Multi-Hole Stop Motion Photography

Using a multi-hole test configuration (30 holes per inch), several photographs of fibers exiting the die were made using a Nikon 35mm camera and two EG&G microflashes whose flash duration was 0.5 microseconds. Figure 4.1 shows the location of the camera and strobes with respect to the extruded fibers. The polymer used for this study was a standard Exxon 400 MFR resin. To examine the effects of polymer throughput on the fiber's in-plane dynamics, two different polymer throughputs (0.8 and 1.2 grams/minute per hole) were investigated. For each throughput, the air velocity was increased in steps from a low 143 meters/second to a high of 330 meters/second. At each stepped increase, a photograph was taken. Lastly it should be noted that, in some of the photographs, a measuring scale was placed next to the exiting fibers in order to establish a common frame of reference.

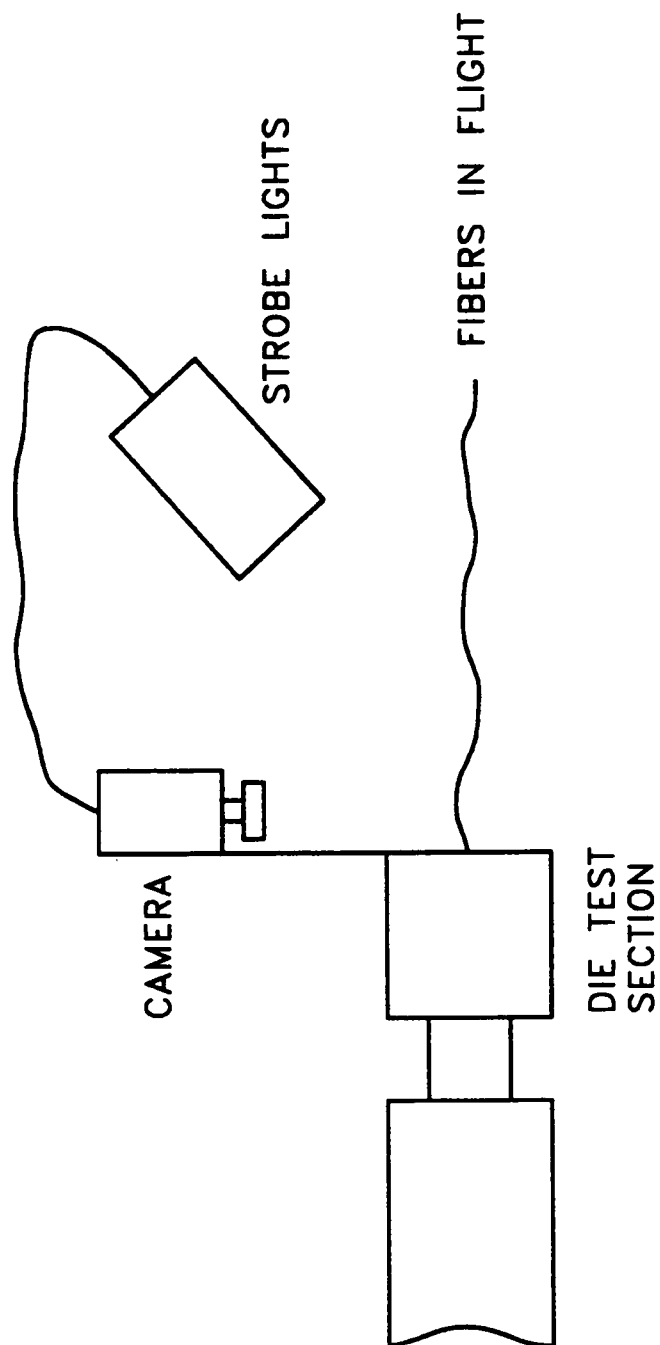


Figure 4.1: Side view of extruder showing the location of the camera and strobe lights used to obtain stop motion pictures.

Single Fiber Plane Motion

After using the 35mm camera to look at the movement of multiple fibers, it was decided that an examination of a single fiber using a video camera would be beneficial. Figure 4.2 depicts the setup used to capture and analyze the single fiber data. This setup included a video camera with a 55mm zoom lens, a 4-head Magnavox VCR, an A/D video frame capture board, a 386 IBM compatible computer, and a Sony Trinitron flat screen tv. The polymer used was a 1000 MFR resin (1000-C from Chapter III). Video recordings were made at polymer throughputs of 0.8 and 1.2 grams/minute per hole and air velocities ranging between 121 and 330 meters/second. Once a recording was made, it was then played back through the video frame capture board where a FORTRAN code would "grab" random frames off the tape playback in a consecutive order. These frames were then digitized and stored on the computer's hard drive as a TIFF-G graphics file. To analyze the fiber's plane motion, an imaginary axes was attached to the Sony Trinitron's flat screen. These axes allowed measurements to be made at four locations (0.159, 0.292, 0.422, and 0.55 inches from the die exit plane) perpendicular to the fiber's flow direction; thus, showing how the fiber deviated from an ideal imaginary centerline axis. Using these attached axes, the saved graphics files (frames) were then recalled and examined in the order they were recorded. As each file was examined, the fiber's position (in inches) in relation to the imaginary centerline axis, either left or right of the line, was noted for each of the four axes locations. Therefore in the end, a visualization of the fiber's transverse motion back and forth across the imaginary centerline axis was made at a distance less

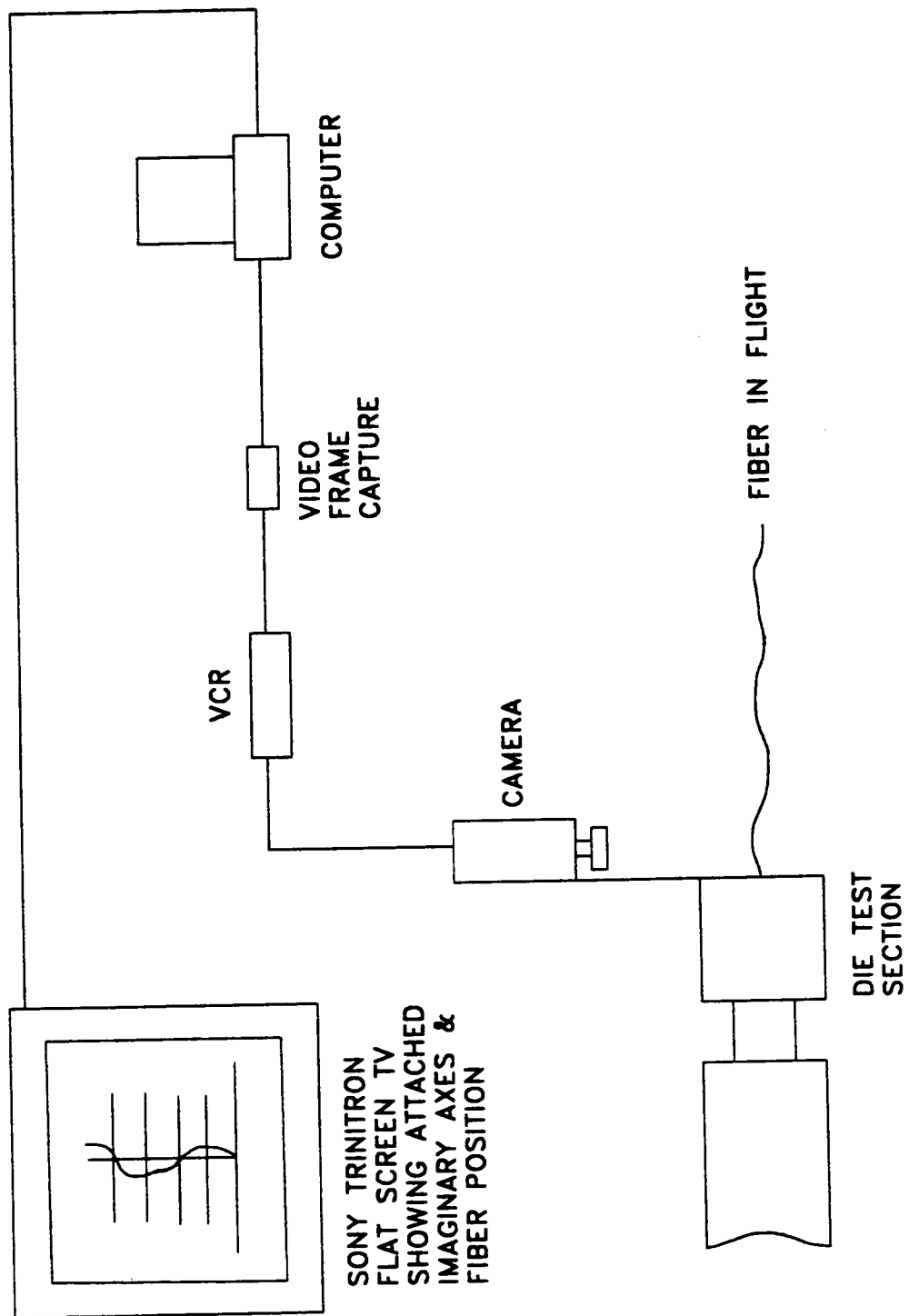


Figure 4.2: Side view of extruder showing the location and set-up of the video camera and frame capture equipment.

than 0.75 inches from the die exit plane. Again, as with the multi-hole photos, pictures of various scaled material were placed next to the exiting fiber in order to establish a frame of reference for distance measuring purposes.

Experimental Investigation of a Converging Nozzle Flowfield

Various researchers [3,6,8, and 18] have demonstrated that, while using the melt blowing process, the increasing of the air velocity leads to a decrease in the average fiber diameter of the collected webs. Haynes [18] explains that one reason for this can be attributed to the interaction of the fibers with the varying centerline velocities of the melt blown jet configuration. Therefore an investigation of the jet flowfield was performed in order to gain a better understanding of how the centerline velocities changed with distance from the die exit plane. This part of the chapter is broken up into three sections. Together these sections describe the equipment and procedures used to measure the changing flowfield velocities. The first section, Instrumentation, is a description of the equipment set-up used to collect data. The second section, Axis Coordinates and Measuring Orifice Delta Pressures, details the location of the three dimensional coordinate system, the specific test conditions that were examined, and the procedures used to collect and reduce pressure measurements. The last section, Uncertainty, is a brief statement concerning the uncertainty of the measuring devices.

Instrumentation

To determine the centerline velocities, a 90 degree pitot tube was mounted onto a vertical linear displacement screw, which in turn was attached to a large metal framework. This framework was then placed in front of, i.e., downstream of the die test section. The framework's large mass helped to provide a stable base, which minimized vibrations due to the flow of air over the pitot tube. The amount of displacement of the linear screw was controlled using a stepper motor. This motor could be stepped in increments resulting in vertical displacements of the probe as small as 0.005 inches. The pitot tube was connected to an analog pressure transducer (APT) with a pressure measuring capability between 0 and 20 pounds per square inch. The APT was calibrated using a mercury manometer. For ease of use, the APT was hooked up to a digital readout that displayed measured pressures in pounds per square inch. Figure 4.3 shows a drawing of the complete measuring system. Finally, compared to other pressure probes, a 90 degree pitot tube was used because it would produce the least amount of interference with the flowfield at the location being measured.

Axis Coordinates and Measuring Orifice Delta Pressures

Since the air jet flowfield was the primary concern of this investigation, no polymer was extruded while pressure measurements were being made. As mentioned in Chapter II, an orifice upstream of the die test section was used to determine the mass flow rate of the air leaving the nozzle, which in turn, allowed the velocity at the nozzle exit to be

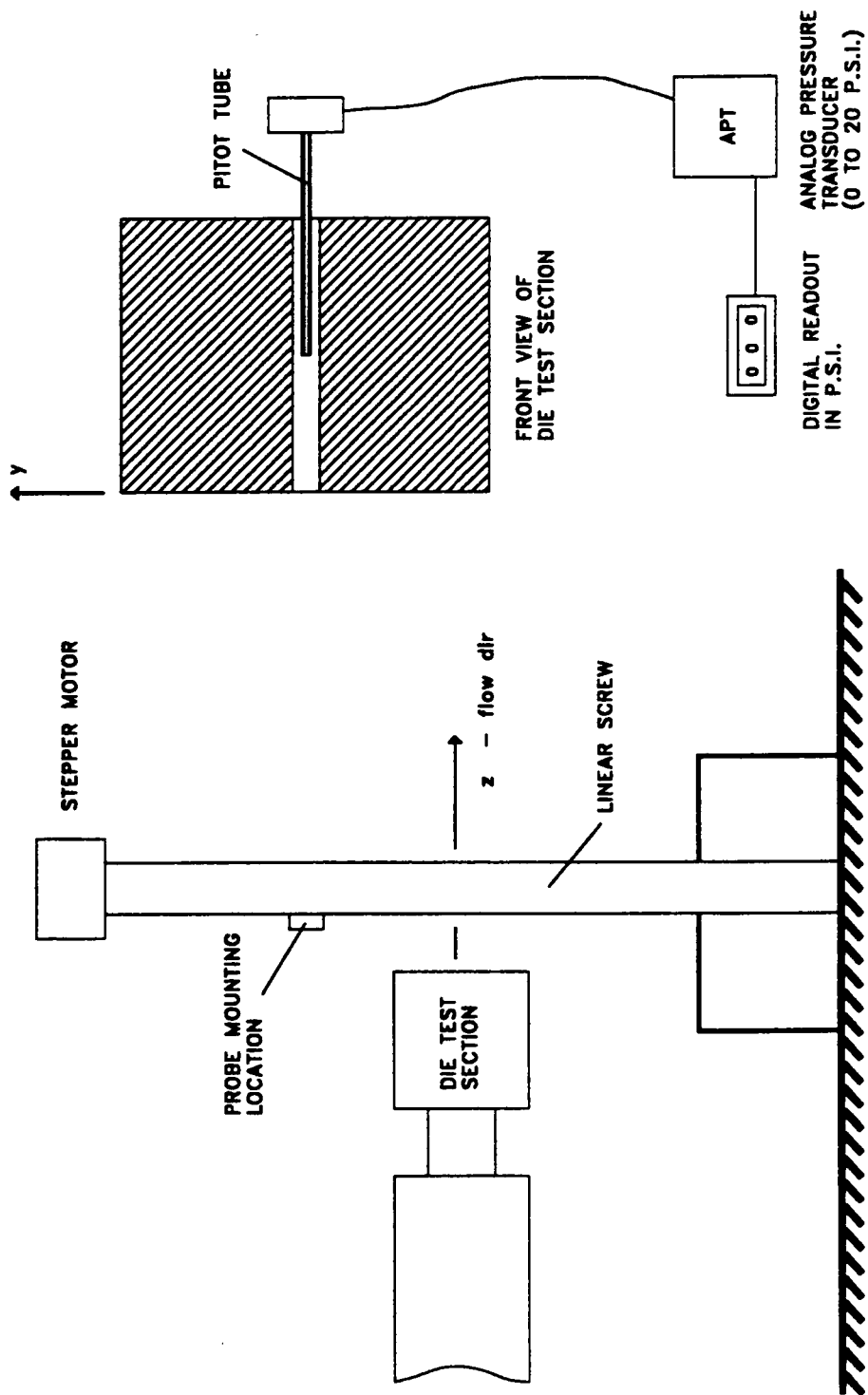


Figure 4.3: Sketch of the pressure measuring set-up used to determine the free jet centerline velocities.

calculated. The exit velocities were determined by the h_m (in inches of water) readings of the measuring orifice gage. The h_m settings were achieved using the manual throttling valve located downstream of the measuring orifice. During this study, measurement orifice gage readings of 2, 5, and 12 inches of water were used. At an air stagnation temperature of 73 degrees Fahrenheit, these readings corresponded to exit air velocities calculated from Equation 2.4 of 78, 120, and 180 meters/second respectively. For reference purposes, a three dimensional axis system was attached at the die exit plane as shown in Figure 4.4. This figure depicts the z-axis as being away from the die exit plane, the y-axis as being in the upward vertical direction, and the x-axis traversing the die exit plane. Therefore, since the overall depth of the die exit width is 4 inches, a location of $x = 2$, $y = 0$, $z = 0$ inches would be directly in the center of the die exit plane, as viewed from the front. To make measurements in the y-direction, the stepper motor was used; but, to make measurements in the z-direction, the framework had to be moved in accordance with scaled markings on the floor. A similar technique was used for the x-direction except that these markings were located on the pitot tube itself.

After all the pressure measurements were made, Bernoulli's equation was then used to find the velocities. Bernoulli's equation states [19]:

$$V_{fj} = \sqrt{\frac{13790(\Delta P_{\text{pitot}})}{\rho_{\text{air}}}} \quad 4.1$$

where: V_{fj} velocity of the free jet in meters per second

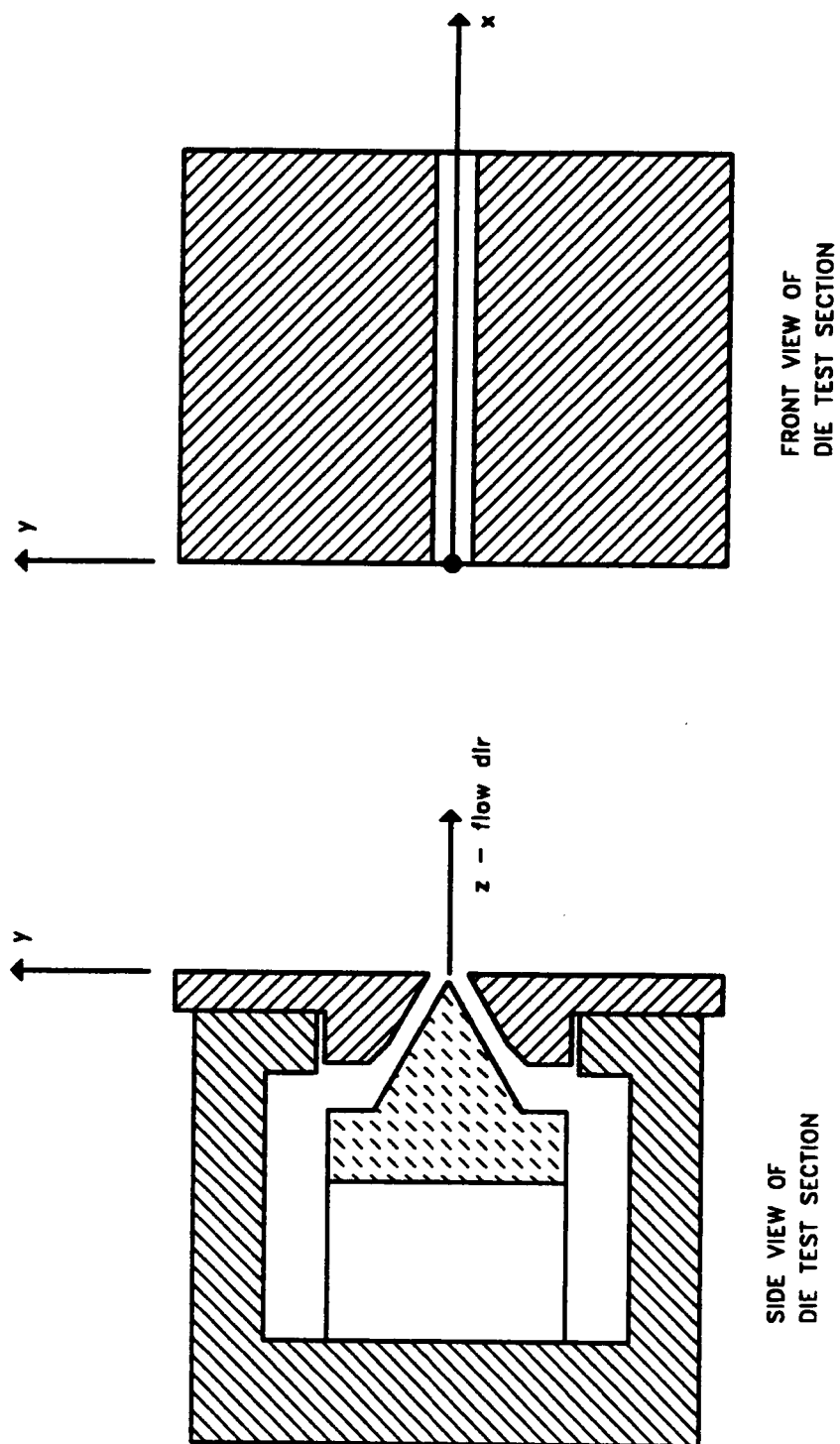


Figure 4.4: Location of the three dimensional axis used for measuring the free jet's flowfield pressures.

ΔP_{pitot} pressure reading from the APT in p.s.i.

ρ_{air} density of air in kilograms per meter cubed

This equation is subjected to the restrictions of steady flow, no friction, flow along a streamline, and incompressible flow.

Uncertainty

The least count of the digital readout connected to the APT was ± 0.01 pounds per square inch. Consequently, the uncertainty of the readout was approximately ± 0.005 pounds per square inch. The uncertainty of the temperature measurement was approximately ± 1.4 degrees Fahrenheit. Therefore, based on both the pressure readout and the temperature uncertainty, the uncertainty of the velocity was estimated to be ± 4 meters/second.

CHAPTER V

EXPERIMENTAL INVESTIGATION OF ALTERNATE NOZZLE CONFIGURATIONS RESULTING IN SUPERSONIC FLOW

It is well established that the smaller the web fiber diameters, the higher the web filtration efficiency. This has led to an overwhelming demand for the production of small fibers (typically < 1 micron in diameter). Currently, fibers this small are made by extruding polymer at low throughputs (usually < 0.8 grams/minute per hole). This, however, limits companies in their amount of polymer production. This limitation can cause major complications; especially if, in the future, a company desires to increase its product output to increase revenues or simply to meet public demand. Therefore, the need to produce small fibers at throughputs as high as 1.2 grams/minute per hole is of prime importance. The current investigation is a first step towards this goal.

As stated in the last chapter, many researchers have discovered that, as the velocity of the converging streams of heated air is increased, the average fiber diameters of the collected webs decrease. Since the typical melt blowing air nozzle configuration resembles a converging nozzle, the highest velocity that can be obtained at the nozzle exit is the speed of sound. At this condition, the nozzle is said to be "choked." A choked nozzle is defined by having a Mach number of unity at the nozzle exit plane. To overcome this limitation on velocity at the nozzle exit, the converging nozzle must be replaced with a converging-diverging nozzle (c-d nozzle). With this type of nozzle, speeds in excess of

Mach one (supersonic) can be achieved at the exit. In addition, the choking effect now occurs at the throat of the converging-diverging nozzle; i.e., the throat of a c-d nozzle whose exit velocities are supersonic has a Mach number of one. Three possible advantages of using a c-d nozzle would be (1) the establishing of a more uniform exit flowfield, thus, decreasing the chance of fibers to interact (collide) with one another close to the die's exit plane and (2) the production of fibers (at high polymer throughput rates) whose diameters are smaller than 1 micron, thus, increasing web filtration efficiencies and (3) due to the size of the die orifice hole spacing, by producing smaller fibers, fiber collisions upon extrusion from the die test section would possibly be reduced. The replacing of the converging nozzle with a converging-diverging nozzle is the focus of this chapter. The chapter is broken up into four main sections. These sections are Extension Plates, Downstream Converging-Diverging Nozzle, Modified Downstream Converging-Diverging Nozzle, and Upstream Converging-Diverging Nozzle.

Extension Plates

Before looking at any type of physically contoured converging-diverging nozzle, two 1/2 inch adjustable flat "extension" plates were bolted onto the front of the multi-hole die test section. Through viscous effects (boundary layer growth), these flat plates essentially created a crude, inexpensive c-d nozzle. A drawing of this configuration, showing an exaggerated extension plate width spacing, can be seen in Figure 5.1. The

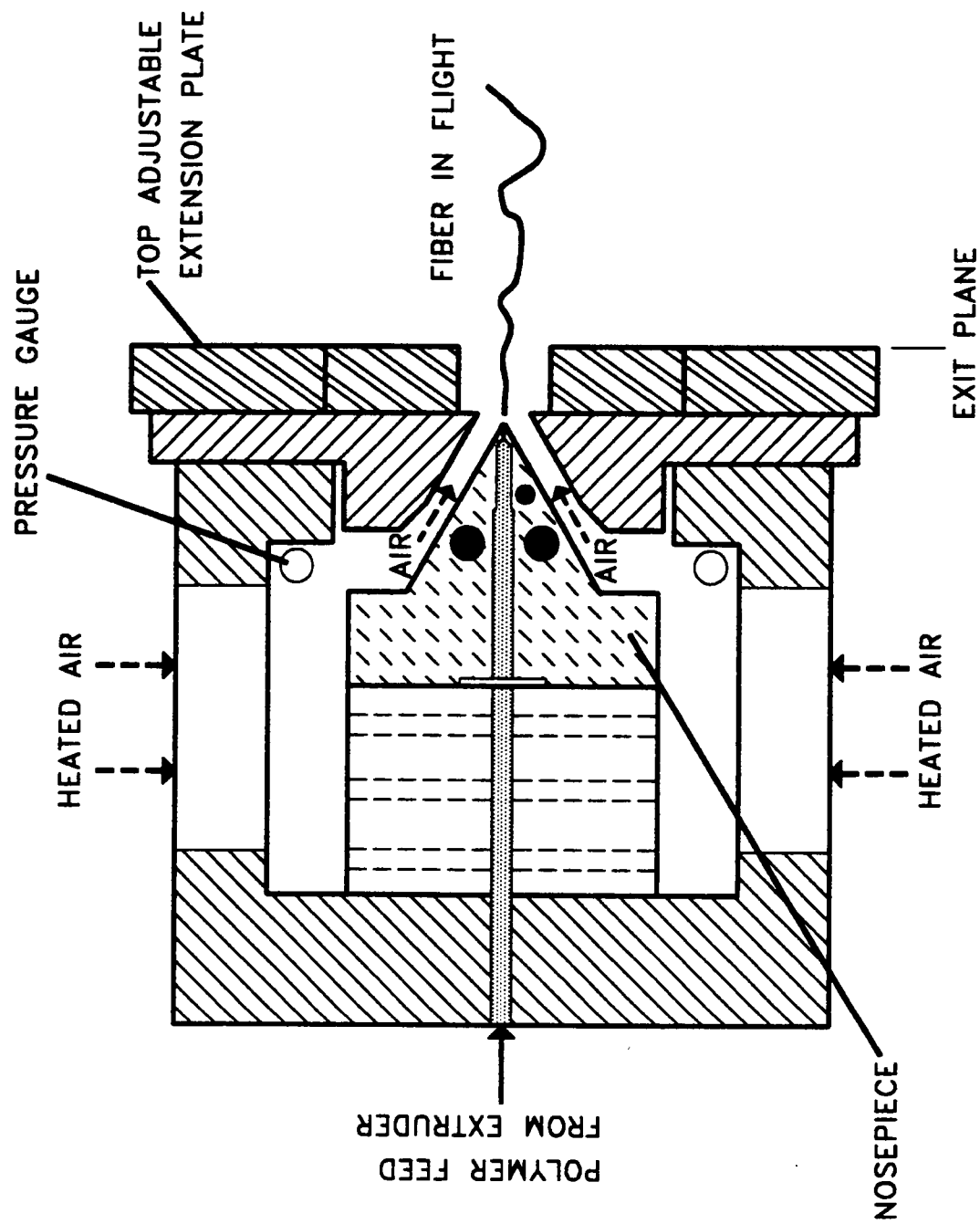


Figure 5.1: Cross-sectional view of the die test section with converging nozzle face plates and added extension plates.

overall test conditions used during this study were identical to those used in Chapter III - Investigation of Changes in Polymer Temperature. That is, a 1000 MFR polymer resin was used at polymer temperatures ranging from 364 to 450 degrees Fahrenheit, while the air temperature was held at a constant 400 degrees Fahrenheit. The polymer throughput was 0.8 grams/minute per hole.

Downstream Converging - Diverging Nozzle

Having used the extension plates, the next logical step was to actually design and build a physically contoured c-d nozzle. Initially it was decided that the new nozzle should not drastically deviate from the typical shape of the classical converging nozzle; thus, allowing for easy integration of the nozzle into existing industry melt blowing systems. Therefore, parameters such as die setback, air gap, and exit width as described in Chapter II were the basic parameters that the new nozzle was designed around. By keeping these parameters constant, the new c-d nozzle was essentially the typical converging nozzle with an added contoured divergent section attached at the die exit plane. By adding this divergent section, the exit of the old converging nozzle now becomes the throat of the new c-d nozzle. Concerning the title of this section, the term "downstream" refers to the location of the c-d nozzle throat with respect to the tip of the die nosepiece.

Although the attaching of a divergent section to an already existing nozzle may sound like a simple task, many complications arise when trying to determine the wall

contour of such a section. Although there are several ways to determine the wall contour of a c-d nozzle divergent section, the most popular way is to use a method based on the turning of flow through small angles. This method is called the Method of Characteristics: Region-to-Region Method [17]. This method has been used extensively in the design of large supersonic wind tunnels. Saad [20] describes the method of characteristics as indicating the properties of a compressible fluid in which continuous waves of small but finite amplitude are present as the fluid flows supersonically, irrotationally, and shock-free. For the 2-D region-to-region method [17], the continuous flow field is divided into regions of uniform flow divided by weak but finite waves. These weak waves are called characteristic or Mach waves. Property changes across these waves can be determined using linear theory to transform the equations of flow (mathematical expressions which describe the motion of compressible fluids) from partial differential equations to ordinary differential equations [20]. Since this is an approximate method, as the number of regions that the flow is divided into is increased, a more exact solution (contour of the divergent wall) is attained.

There were two variations of the method of characteristics that were used in the designing of the nozzle divergent section. These were (1) the designing of a minimum length nozzle using the region-to-region method and (2) the classical region-to-region method. The first technique was used in the hopes that a small divergent section would dramatically decrease the chance of polymer fibers to collide with the nozzle wall. This method assumes that all of the incident characteristics occur as a Prandtl-Meyer expansion fan at the throat. These weak waves are then reflected and canceled by the contouring of

the nozzle wall downstream. When this method was applied using the desired nozzle throat width of 0.107 inches (equal to the converging nozzle die exit width) for an exit Mach number 1.5, the method appeared to work too well. The overall length of the divergent section (from throat to exit) turned out to be only 0.1175 inches. It is of no doubt that a divergent section this small, with a smoothly contoured wall, would be almost impossible to make. Consequently, the second technique, the classical region-to-region method, was used to see if larger nozzle lengths could be obtained. The classical method assumes that the incident characteristics occur at incremented steps from the nozzle wall immediately downstream of the throat. Like in the minimum length method, these incident waves are reflected and then canceled downstream, thus determining the nozzle wall contour. Again, the method was employed using the exit width of the converging nozzle as the throat width for this nozzle. Due to steep reflection angles caused by such a small throat height ($1/2$ the throat width of 0.107 inches), the results obtained from this method fared no better than those calculated using the minimum length method. Therefore, a contoured shape was designed using 2 degree expansion segments, with the intention that boundary layer growth would play a major role in the decreasing of the nozzle's exit width [21]. This design was then taken to a machine shop where it was cut out of a block of cold rolled steel using a wire EDM (Electrical Discharge Machining). The final shape having an exit to throat area ratio of 2.43, a divergent section length of 0.872 inches, and an overall length of 1.749 inches is shown in Figure 5.2. A more detailed drawing of this nozzle can

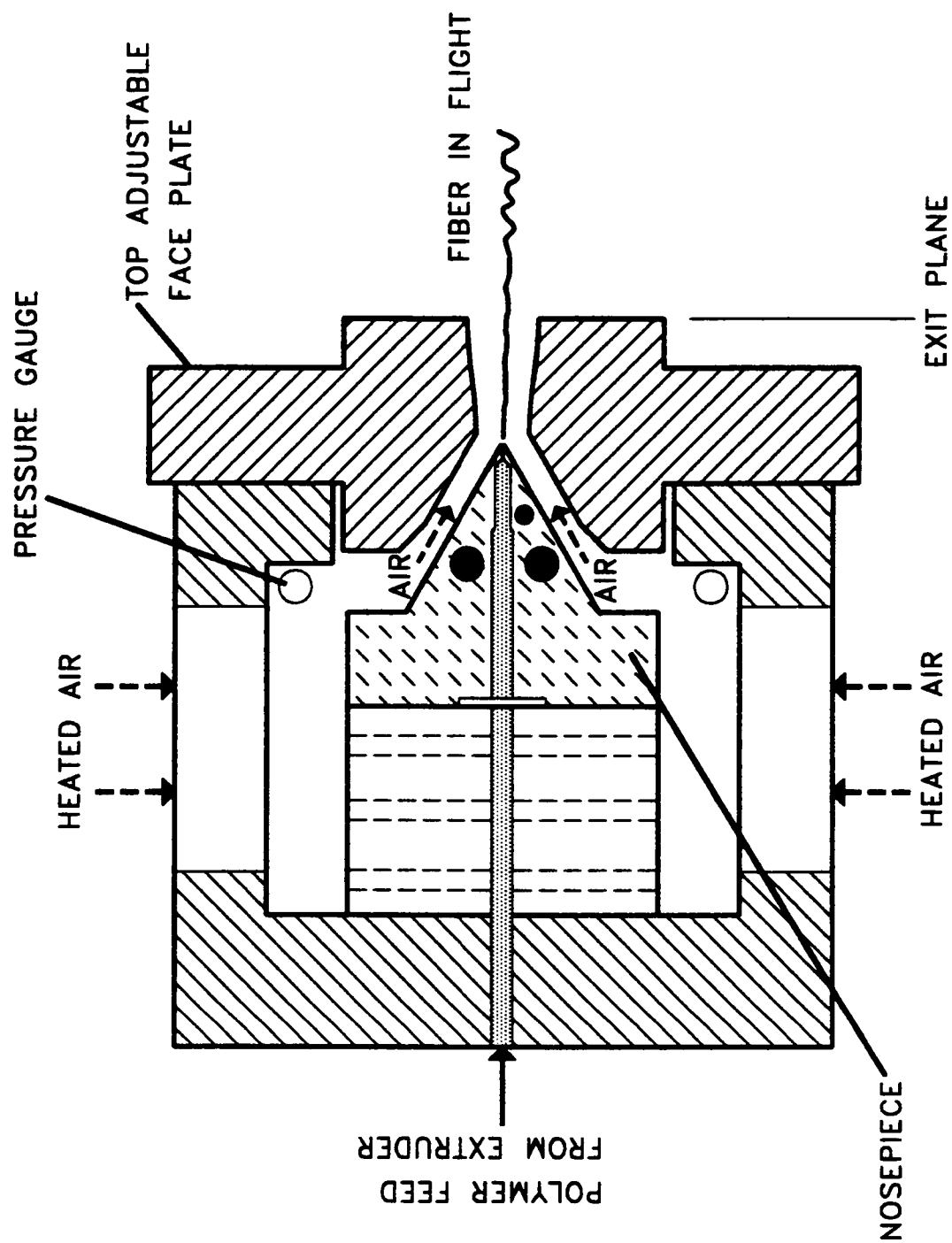


Figure 5.2: Cross-sectional view of the die test section showing the new downstream converging - diverging nozzle.

be seen in Appendix Figures A1 and A2. Having been stated several times already, Figure 5.3 shows that the throat width of the new c-d nozzle is simply the exit width of the old converging nozzle.

Once the new nozzle was installed to the multi-hole die test section, it was important to know if the flow leaving the nozzle was actually supersonic. To determine this, collimated light was used to examine the flow for density gradients such as diamond shock waves. The use of collimated light in such a way is commonly called a shadowgraph. A detailed explanation of the shadowgraph technique is given by Haynes [18]. Finally, only one polymer, an 800 MFR resin (800-F from Chapter III - Investigation of Various Polymers), was used during this investigation. Web samples were collected using polymer throughputs of 0.8 and 1.2 grams/minute per hole; the polymer and air temperatures examined ranged from 400 to 600 degrees Fahrenheit. In order to meet the stagnation pressure demands required to achieve supersonic flow at the nozzle's exit, the pressure regulator of the air supply system was increased from a gage pressure of 50 psi to a value of 70 psi.

Modified Downstream Converging - Diverging Nozzle

Multi-Hole Die

After making various runs with the downstream converging-diverging nozzle described in the previous section, it was then decided to see what affect milling 1/4 inch of

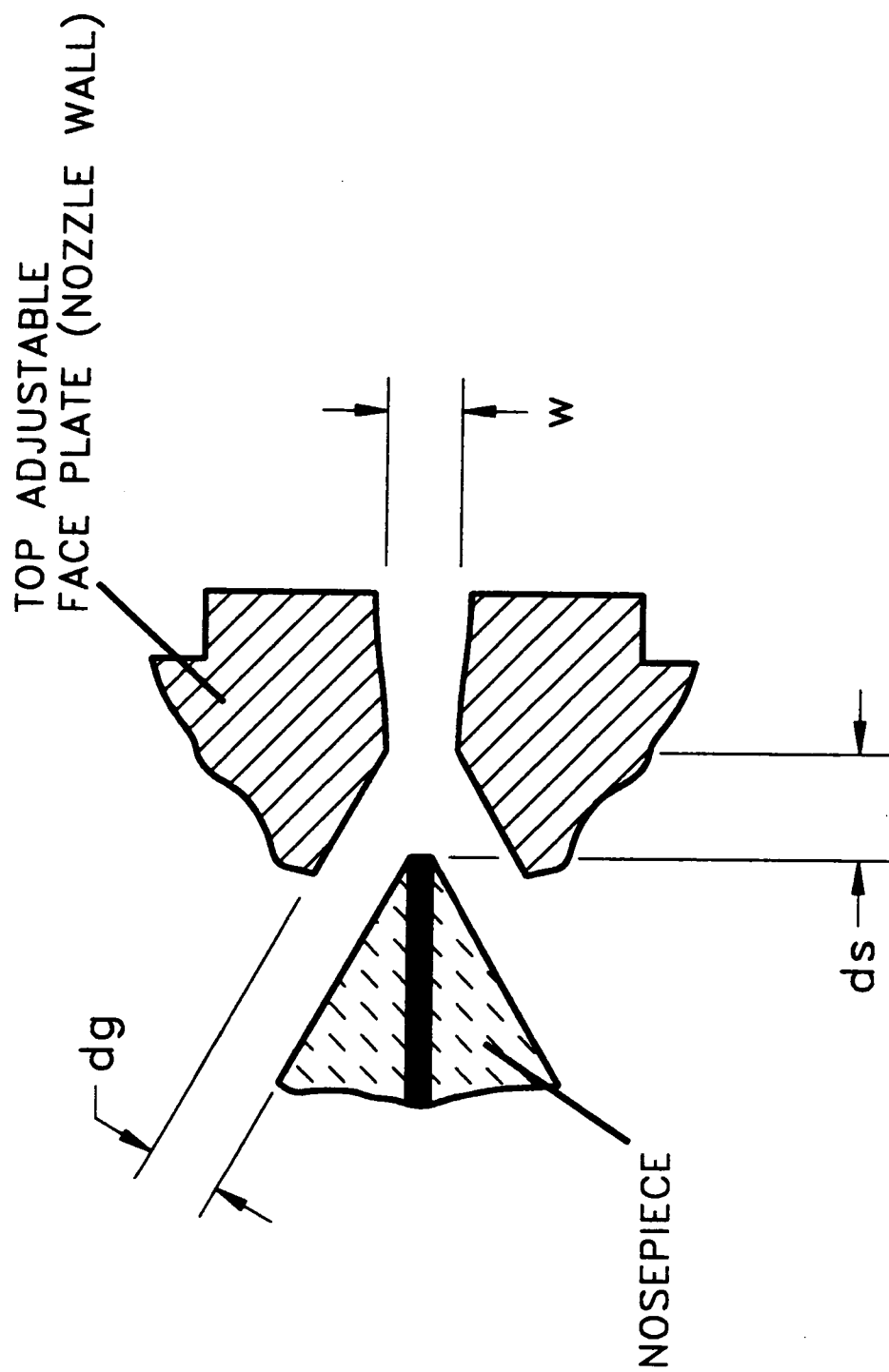


Figure 5.3: Geometrical layout of the downstream converging - diverging nozzle.

material off the nozzle's exit plane would have on the production of small fibers and shot. Figure 5.4 shows a cross-sectional drawing of this nozzle attached to the die test section. Having removed 1/4 inch of material, the new exit to throat area ratio became 2.18, the length of the divergent section became 0.622 inches, and the overall nozzle length became 1.449 inches. The test conditions and sample collection procedures used for this study were identical to those used previously for the unmodified downstream nozzle.

Single-Hole Die

By having polymer fibers being extruded into a supersonic stream of heated air, the overall system becomes a complex fiber and air flowfield. Therefore, complications may arise when these fibers start generating their own shock waves within the nozzle, thus, creating havoc with the existing supersonic flow stream. With this in mind, to see what effect, if any, the reduction in the number of polymer fibers being extruded would have on the average fiber diameter, the multi-hole die was removed and replaced with the single-hole die. Also it should be noted that without the multi-hole die, neighboring fiber collisions will not occur. The test conditions were identical to the multi-hole case.

Upstream Converging - Diverging Nozzle

After reviewing the data collected with the downstream converging-diverging nozzle, it was decided to develop an upstream converging-diverging nozzle. The biggest

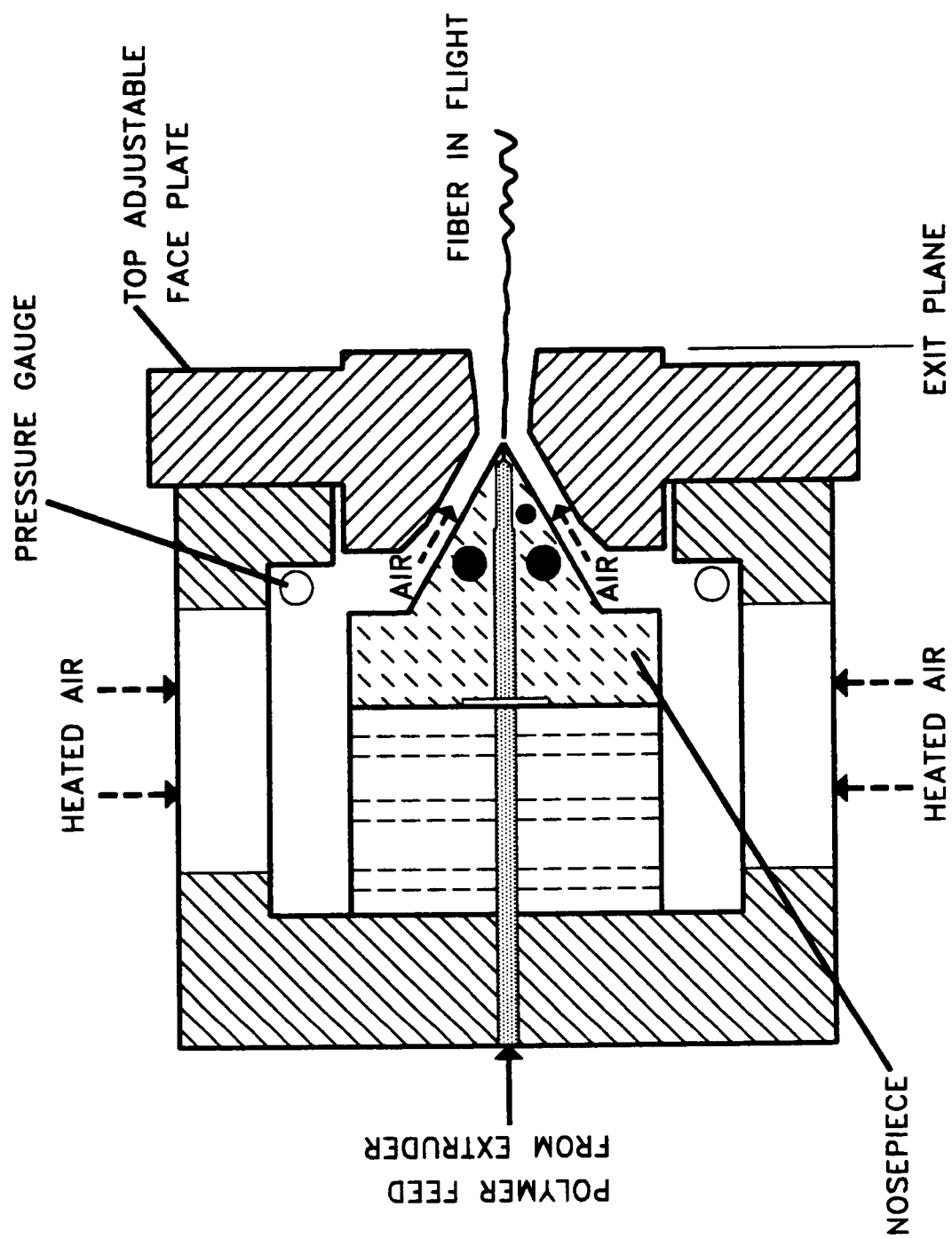


Figure 5.4: Cross-sectional view of the die test section showing the modified downstream converging - diverging nozzle.

advantage of the upstream nozzle is that the polymer exiting the nosepiece exits into an already established supersonic flow stream. As can be seen, this is a completely different situation than what the downstream nozzle experienced; i.e., the polymer exiting the nosepiece had to first traverse the sonic line located at the nozzle's throat before entering the supersonic flow of the nozzle's divergent section. As with the downstream nozzle, after determining a contour for the nozzle's wall, wire EDM was used to cut the shape out of a block of cold rolled steel. Figure 5.5 shows a side view of this nozzle attached to the die test section. The exit to throat area ratio for this nozzle configuration was 1.45, with a divergent section length of 0.788 inches. The overall nozzle length was 1.01 inches. It should be apparent from this figure that the nozzle now is oriented along the 60 degree nosepiece and that the air gap value has become the nozzle throat height. A more detailed drawing of this nozzle is shown in Appendix Figures A3 and A4.

Multi-Hole Die

As with all the previous supersonic nozzle configurations, similar test conditions and procedures were used for this study with the exception of the polymer throughput rate. The polymer used was an 800 MFR (800-F from Chapter III), the air and polymer temperatures were varied from 400 to 600 degrees Fahrenheit, and the polymer throughput was set at 1.2 grams/minute per hole. The throat height or air gap value was set at 0.04 inches.

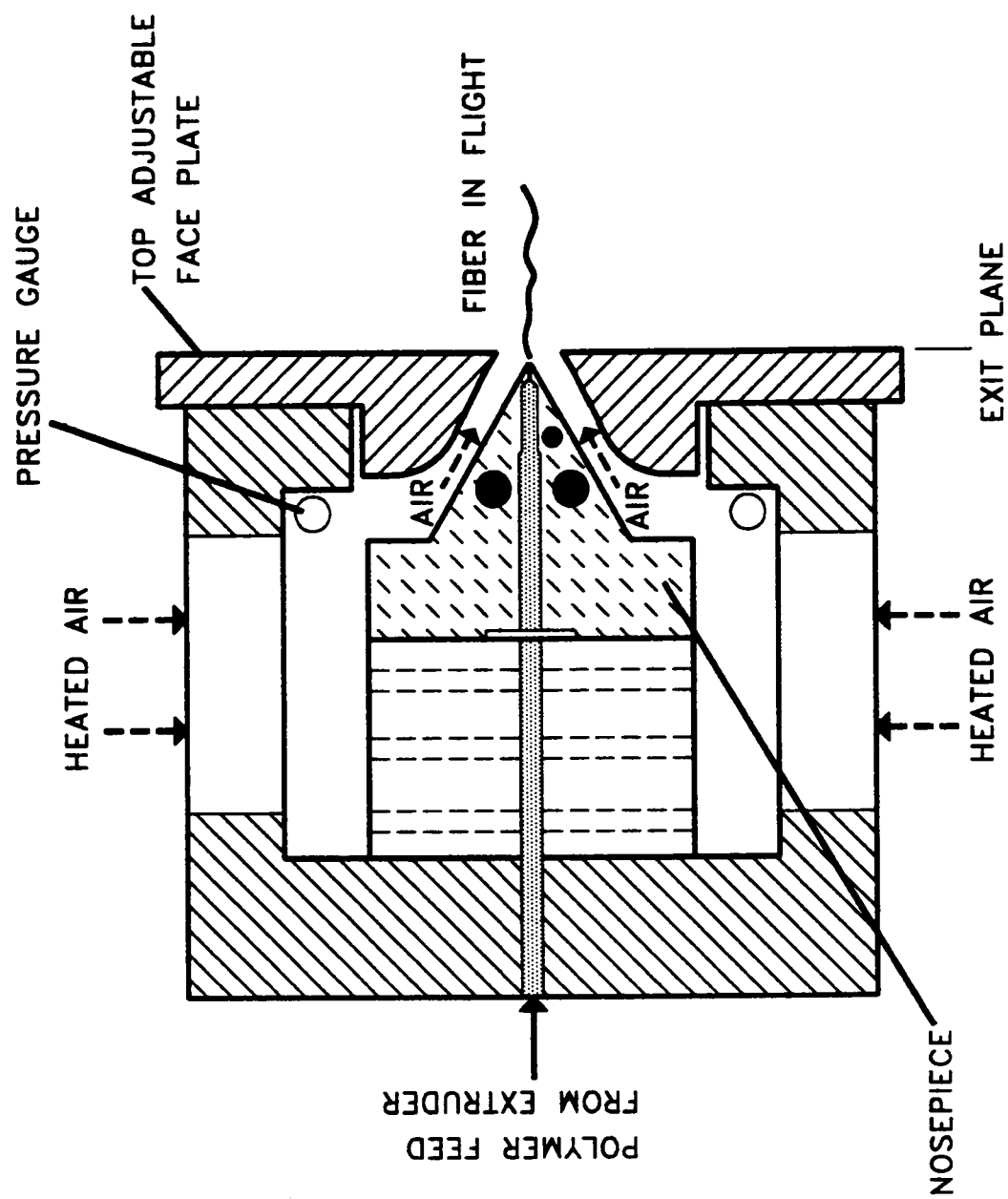


Figure 5.5: Cross-sectional view of the die test section showing the upstream converging - diverging nozzle.

Single-Hole Die

The multi-hole die was replaced with the single-hole die for the same reasons that were stated in the Single-Hole Die section for the modified downstream nozzle. Again, polymer throughput was set at 1.2 grams/minute per hole and the air gap remained at 0.04 inches.

CHAPTER VI

EXPERIMENTAL RESULTS

Chapters III through V outlined the various procedures and configurations which were used to investigate the effect of polymer MFR, fiber interactions, polymer temperature, and air velocity on the production of shot and small fiber diameters. This chapter presents the results that were obtained for each of these investigations.

Investigation of Polymer Characteristics

The following two sections describe the results obtained for the investigations related to the use of various polymers and how changes in polymer temperature affected the shot and fiber characteristics of the web samples.

Investigation of Various Polymers

One very important fact that needs to be mentioned about this study is that, for all of the following MFR cases, most of the samples collected were collected prior to the development of the shot intensity measuring technique. Consequently, most of the samples collected were approximately 1 ounce per square yard in weight. Although, this web size was in accordance with the weight required to determine shot rating values as described in

Chapter II, it proved to be too great for the microscope's light source to completely penetrate the web sample in order to perform shot intensity measurements. Unfortunately, due to time constraints and limited amounts of some of the polymers, these runs could not be redone. Therefore, a web thickness classification for each sample was created. For this scheme, the web sample was classified as either thin, medium, or thick. Thin samples were less than 1 ounce per yard and the shot particles were easily seen completely through the web. For the medium samples, shot could be seen through the web in some places, but, not in others. For the last classification termed thick, the shot particles were usually seen only on one side of the sample and not on the other. In other words, if the 1 inch square sample was turned over to the other side, shot particles that were counted on the initial side would usually not be counted again on the new side due to the web's thickness. This variation in web thickness created problems with how the shot intensity values should be calculated. It was finally decided that, for the thin and medium samples, the shot intensity values would be calculated for each side of the sample and then averaged. Shot intensity values for the thick samples were looked at in two different ways. They were first averaged, like the thin and medium samples, assuming that some of the shot particles could be seen through the web. Next they were added, assuming that none of the shot particles counted on one side was counted a second time on the other side. Some of the sample results reported do not have shot rating values. This was primarily due to the long turn-around times required to obtain results from TANDEC technicians. These technicians were typically back logged with large amounts of work. Therefore, since the shot intensity

scheme required a shorter turn-around time and was more quantitative in nature, it was decided to use this technique instead of the shot rating scheme.

400 MFR

Results for the 400 MFR resin investigation are listed in Table 6.1 and Table 6.2. Table 6.1 shows results obtained for the case of averaging shot intensity values for the thick samples. In Table 6.2, the shot intensity values were added instead of averaged for the thick samples. As can be seen from Table 6.1, for each 400 MFR polymer at both 0.8 and 1.2 grams/minute per hole, the average fiber diameters decrease as the air velocity increases. This finding is consistent to that of many other researchers [3, 6, 8, 14, and 18]. A similar trend can be seen for shot rating and shot intensity values for polymers 400-A and 400-B. This suggests that not only does the average fiber diameter decrease with increased air velocity, but so does the amount of shot present within the web sample. This was not the case for Polymer 400-C, however. This polymer followed the decreasing fiber diameter trend, but not the decreasing shot trend. As the air velocity increased, the shot intensity for 400-C increased in value rather than decreased like polymers 400-A and 400-B. This discrepancy could be attributed to the thickness of the web samples and the subjectivity of the technique. Upon examination of the 400 MFR results, there was no apparent outstanding characteristic that was observed for any of the three polymer resins studied. For the case of adding the thick samples shown in Table 6.2, similar conclusions to those of Table 6.1 can be noted.

Table 6.1: Results obtained for the investigation of various 400 MFR polymers, where the thick web samples were averaged. $T_{air} = T_{poly} = 550^{\circ}F$.

Throughput	400 - A	400 - B	400 - C
0.8 gpm/hole			
Vair = 143 m/s:			
avg. fiber dia.(microns)-	9.1	5.9	6.7
shot intensity avg. -	20.2	40.2	2.8
shot rating -	1.0	3.0	-
web sample thickness -	thin	thin	thin
Vair = 220 m/s:			
avg. fiber dia.(microns)-	4.0	2.9	3.0
shot intensity avg. -	7.9	2.3	17.2
shot rating -	1.0	1.0	-
web sample thickness -	thin	thin	thin
Vair = 327 m/s:			
avg. fiber dia.(microns)-	2.8	1.9	2.6
shot intensity avg. -	3.5	3.9	1.7
shot rating -	0.5	0.5	-
web sample thickness -	thin	thin	thick
1.2 gpm/hole			
Vair = 143 m/s:			
avg. fiber dia.(microns)-	11.5	4.5	13.3
shot intensity avg. -	23.3	34.6	1.4
shot rating -	3.5	3.0	-
web sample thickness -	thin	thin	thin
Vair = 220 m/s:			
avg. fiber dia.(microns)-	5.6	3.9	4.7
shot intensity avg. -	19.7	5.2	9.6
shot rating -	1.0	0.5	-
web sample thickness -	thin	thin	thin
Vair = 327 m/s:			
avg. fiber dia.(microns)-	3.9	2.7	3.5
shot intensity avg. -	7.1	3.1	10.8
shot rating -	0.5	0.5	-
web sample thickness -	thin	thin	thick

Table 6.2: Results obtained for the investigation of various 400 MFR polymers, where the thick web samples were added. $T_{air} = T_{poly} = 550^{\circ}\text{F}$.

Throughput	400 - A	400 - B	400 - C
0.8 gpm/hole			
Vair = 143 m/s:			
avg. fiber dia.(microns)-	9.1	5.9	6.7
shot intensity avg. -	20.2	40.2	2.8
shot rating -	1.0	3.0	-
web sample thickness -	thin	thin	thin
Vair = 220 m/s:			
avg. fiber dia.(microns)-	4.0	2.9	3.0
shot intensity avg. -	7.9	2.3	17.2
shot rating -	1.0	1.0	-
web sample thickness -	thin	thin	thin
Vair = 327 m/s:			
avg. fiber dia.(microns)-	2.8	1.9	2.6
shot intensity avg. -	3.5	3.9	3.4
shot rating -	0.5	0.5	-
web sample thickness -	thin	thin	thick
1.2 gpm/hole			
Vair = 143 m/s:			
avg. fiber dia.(microns)-	11.5	4.5	13.3
shot intensity avg. -	23.3	34.6	1.4
shot rating -	3.5	3.0	-
web sample thickness -	thin	thin	thin
Vair = 220 m/s:			
avg. fiber dia.(microns)-	5.6	3.9	4.7
shot intensity avg. -	19.7	5.2	9.6
shot rating -	1.0	0.5	-
web sample thickness -	thin	thin	thin
Vair = 327 m/s:			
avg. fiber dia.(microns)-	3.9	2.7	3.5
shot intensity avg. -	7.1	3.1	21.6
shot rating -	0.5	0.5	-
web sample thickness -	thin	thin	thick

800 MFR

Tables 6.3 and 6.4 show the results obtained for the 800 MFR resins. As in Table 6.1, Table 6.3 lists results pertaining to the case of averaging shot intensities for thick samples. Looking at Table 6.3, it can be seen that the fiber diameters, shot rating, and intensity values decrease as the air exit velocity increases for both 0.8 and 1.2 grams/minute per hole. This result is similar to the one found in the previous 400 MFR investigation. Again, for the case of averaging shot intensities for thick samples, no apparent major distinctions were found for any of the six polymers examined. However, this was not the case for the results found in Table 6.4. Since Table 6.4 relates to the situation of adding shot intensity values for thick samples, the trends demonstrated by the fiber diameters and shot rating values will not change; but, the shot intensity trends will. Two polymers (800-A and 800-E) shown in Table 6.4 did not exhibit the previously mentioned trend of decreasing shot intensity with increasing air exit velocity. For these two polymers, rather than decreasing with increasing air velocity, the shot intensity values tended to rise at intermediate air velocity settings and then fall at the highest air velocity setting. As was stated earlier, for the case of adding shot intensity values of thick samples, it was assumed that none of the shot particles could be seen through the web. Therefore, one possible explanation for this discrepancy could lie in the fact that some of the shot particles were counted twice for the medium air velocity samples; thus, leading to higher shot intensity values.

Table 6.3: Results obtained for the investigation of various 800 MFR polymers, where the thick web samples were averaged. $T_{air} = T_{poly} = 550^{\circ}\text{F}$.

Throughput	800 - A	800 - B	800 - C	800 - D	800 - E	800 - F
0.8 gpm/hole						
Vair = 143 m/s:						
avg. fiber dia.(microns)-	8.1	8.0	8.0	5.9	7.2	6.3
shot intensity avg. -	4.5	26.1	6.6	4.0	6.1	25.9
shot rating -	-	1.5	2.0	1.5	3.5	1.5
web sample thickness -	thin	thin	thin	medium	thin	thin
Vair = 220 m/s:						
avg. fiber dia.(microns)-	1.8	4.0	3.4	3.6	3.5	3.8
shot intensity avg. -	3.2	6.0	1.8	1.6	3.8	7.6
shot rating -	-	1.0	1.5	1.0	3.0	0.5
web sample thickness -	thick	thin	thick	thick	thick	thin
Vair = 327 m/s:						
avg. fiber dia.(microns)-	1.5	2.1	2.3	3.5	2.8	2.9
shot intensity avg. -	2.2	1.6	2.1	0.8	1.4	4.6
shot rating -	-	0.5	1.0	0.5	3.0	0.5
web sample thickness -	thick	thin	thick	thick	thick	thin
1.2 gpm/hole						
Vair = 143 m/s:						
avg. fiber dia.(microns)-	10.0	7.6	10.7	10.4	10.4	11.4
shot intensity avg. -	8.3	25.3	3.6	4.8	6.6	17.3
shot rating -	-	3.0	3.5	4.0	5.0	3.0
web sample thickness -	thin	thin	thin	thin	thin	thin
Vair = 220 m/s:						
avg. fiber dia.(microns)-	3.6	4.8	5.6	5.9	5.2	5.1
shot intensity avg. -	7.7	15.0	3.1	4.3	3.9	12.1
shot rating -	-	1.5	3.5	3.0	4.0	2.0
web sample thickness -	thick	thin	medium	medium	thick	thin
Vair = 327 m/s:						
avg. fiber dia.(microns)-	3.7	2.6	2.5	3.1	2.9	3.8
shot intensity avg. -	5.6	3.8	1.5	1.8	2.1	7.4
shot rating -	-	0.5	2.5	2.0	3.0	1.0
web sample thickness -	thick	thin	thick	thick	thick	thin

Table 6.4: Results obtained for the investigation of various 800 MFR polymers, where the thick web samples were added. $T_{air} = T_{poly} = 550^{\circ}\text{F}$.

Throughput	800 - A	800 - B	800 - C	800 - D	800 - E	800 - F
0.8 gpm/hole						
Vair = 143 m/s:						
avg. fiber dia.(microns)-	8.1	8.0	8.0	5.9	7.2	6.3
shot intensity avg. -	4.5	26.1	6.6	4.0	6.1	25.9
shot rating -	-	1.5	2.0	1.5	3.5	1.5
web sample thickness -	thin	thin	thin	medium	thin	thin
Vair = 220 m/s:						
avg. fiber dia.(microns)-	1.8	4.0	3.4	3.6	3.5	3.8
shot intensity avg. -	6.4	6.0	3.6	3.2	7.6	7.6
shot rating -	-	1.0	1.5	1.0	3.0	0.5
web sample thickness -	thick	thin	thick	thick	thick	thin
Vair = 327 m/s:						
avg. fiber dia.(microns)-	1.5	2.1	2.3	3.5	2.8	2.9
shot intensity avg. -	4.4	1.6	4.2	1.6	2.8	4.6
shot rating -	-	0.5	1.0	0.5	3.0	0.5
web sample thickness -	thick	thin	thick	thick	thick	thin
1.2 gpm/hole						
Vair = 143 m/s:						
avg. fiber dia.(microns)-	10.0	7.6	10.7	10.4	10.4	11.4
shot intensity avg. -	8.3	25.3	3.6	4.8	6.6	17.3
shot rating -	-	3.0	3.5	4.0	5.0	3.0
web sample thickness -	thin	thin	thin	thin	thin	thin
Vair = 220 m/s:						
avg. fiber dia.(microns)-	3.6	4.8	5.6	5.9	5.2	5.1
shot intensity avg. -	15.4	15.0	3.1	4.3	7.8	12.1
shot rating -	-	1.5	3.5	3.0	4.0	2.0
web sample thickness -	thick	thin	medium	medium	thick	thin
Vair = 327 m/s:						
avg. fiber dia.(microns)-	3.7	2.6	2.5	3.1	2.9	3.8
shot intensity avg. -	11.2	3.8	3.0	3.6	4.2	7.4
shot rating -	-	0.5	2.5	2.0	3.0	1.0
web sample thickness -	thick	thin	thick	thick	thick	thin

1000 MFR

The last group of polymers investigated was the 1000 MFR resins. The results of this study are listed in Tables 6.5 and 6.6. Table 6.5 details the findings for the case of averaging shot intensity values. From this table, the reoccurring trend of decreasing average fiber diameters and shot rating values with increasing air velocity (shown for both previous MFR investigations) was present for this investigation as well. In general, this trend was also reflected by the shot intensity values determined for polymers 1000-A, 1000-B, and 1000-C. One resin (1000-D) however, exhibited no apparent shot intensity trend at either 0.8 or 1.2 grams/minute per hole. At the lower throughput rate, the shot intensity value decreased at the intermediate velocity setting; but, then increased at the higher velocity. The opposite was true for the higher throughput rate of 1.2 grams/minute per hole. The same remarks can be made for the case of adding shot intensities for thick samples shown in Table 6.6.

Repeatability

As mentioned in Chapter III, a repeatability study was performed in order to determine if similar web characteristic results could be obtained for a given polymer, tested at similar test conditions of a previous run, on a different day. It should be noted that these conditions only included parameters that were controlled. Parameters such as ambient air temperature and atmospheric humidity are examples of test conditions that were not controlled. Tables 6.7, 6.8, and 6.9 list the results for 400, 800, and 1000 MFR

Table 6.5: Results obtained for the investigation of various 1000 MFR polymers, where the thick web samples were averaged. $T_{air} = T_{poly} = 450\text{ }^{\circ}\text{F}$.

Throughput	1000 - A	1000 - B	1000 - C	1000 - D
0.8 gpm/hole				
Vair = 143 m/s:				
avg. fiber dia (microns)-	-	-	7.4	5.9
shot intensity avg. -	-	-	6.7	4.5
shot rating -	-	-	-	-
web sample thickness -	-	-	thin	thin
Vair = 220 m/s:				
avg. fiber dia.(microns)-	3.5	4.2	3.3	3.5
shot intensity avg. -	4.5	4.2	5.3	1.2
shot rating -	0.5	0.5	-	-
web sample thickness -	thin	thin	thin	thick
Vair = 327 m/s:				
avg. fiber dia.(microns)-	2.7	2.2	2.7	2.5
shot intensity avg. -	1.9	2.9	1.9	2.5
shot rating -	0.5	0.5	-	-
web sample thickness -	thin	thin	thick	thick
1.2 gpm/hole				
Vair = 143 m/s:				
avg. fiber dia.(microns)-	8.2	12.9	7.3	11.3
shot intensity avg. -	23.2	24.4	5.6	5.4
shot rating -	2.0	1.5	-	-
web sample thickness -	thin	thin	thin	thin
Vair = 220 m/s:				
avg. fiber dia.(microns)-	5.3	5.8	4.6	6.7
shot intensity avg. -	10.9	11.8	3.8	8.9
shot rating -	0.5	0.5	-	-
web sample thickness -	thin	thin	thick	thin
Vair = 327 m/s:				
avg. fiber dia.(microns)-	4.1	2.9	2.2	3.3
shot intensity avg. -	4.2	0.8	3.9	2.8
shot rating -	0.5	0.5	-	-
web sample thickness -	thin	thin	thick	thick

Table 6.6: Results obtained for the investigation of various 1000 MFR polymers, where the thick web samples were added. $T_{air} = T_{poly} = 450\text{ }^{\circ}\text{F}$.

Throughput	1000 - A	1000 - B	1000 - C	1000 - D
0.8 gpm/hole				
Vair = 143 m/s:				
avg. fiber dia.(microns)-	-	-	7.4	5.9
shot intensity avg. -	-	-	6.7	4.5
shot rating -	-	-	-	-
web sample thickness -	-	-	thin	thin
Vair = 220 m/s:				
avg. fiber dia.(microns)-	3.5	4.2	3.3	3.5
shot intensity avg. -	4.5	4.2	5.3	2.4
shot rating -	0.5	0.5	-	-
web sample thickness -	thin	thin	thin	thick
Vair = 327 m/s:				
avg. fiber dia.(microns)-	2.7	2.2	2.7	2.5
shot intensity avg. -	1.9	2.9	3.8	5.0
shot rating -	0.5	0.5	-	-
web sample thickness -	thin	thin	thick	thick
1.2 gpm/hole				
Vair = 143 m/s:				
avg. fiber dia.(microns)-	8.2	12.9	7.3	11.3
shot intensity avg. -	23.2	24.4	5.6	5.4
shot rating -	2.0	1.5	-	-
web sample thickness -	thin	thin	thin	thin
Vair = 220 m/s:				
avg. fiber dia.(microns)-	5.3	5.8	4.6	6.7
shot intensity avg. -	10.9	11.8	7.6	8.9
shot rating -	0.5	0.5	-	-
web sample thickness -	thin	thin	thick	thin
Vair = 327 m/s:				
avg. fiber dia.(microns)-	4.1	2.9	2.2	3.3
shot intensity avg. -	4.2	0.8	7.8	5.6
shot rating -	0.5	0.5	-	-
web sample thickness -	thin	thin	thick	thick

Table 6.7: Results obtained for the repeatability of various 400 MFR polymers, where the thick web samples were averaged. $T_{air} = T_{poly} = 550\text{ }^{\circ}\text{F}$.

Throughput	400-A	400-A	400-B	400-B
0.8 gpm/hole	run 1	run 2	run 1	run 2
Vair = 143 m/s:				
avg. fiber dia.(microns)-	9.1	13.1	5.9	4.0
shot intensity avg. -	20.2	7.4	40.2	32.8
shot rating -	1.0	-	3.0	-
web sample thickness -	thin	thin	thin	thin
Vair = 220 m/s:				
avg. fiber dia.(microns)-	4.0	5.6	2.9	5.4
shot intensity avg. -	7.9	4.7	2.3	32.3
shot rating -	1.0	-	1.0	-
web sample thickness -	thin	thin	thin	medium
Vair = 327 m/s:				
avg. fiber dia.(microns)-	2.8	3.8	1.9	3.5
shot intensity avg. -	3.5	2.7	3.9	7.6
shot rating -	0.5	-	0.5	-
web sample thickness -	thin	thick	thin	thick
1.2 gpm/hole				
Vair = 143 m/s:				
avg. fiber dia.(microns)-	11.5	17.2	4.5	-
shot intensity avg. -	23.3	4.3	34.6	-
shot rating -	3.5	-	3.0	-
web sample thickness -	thin	thin	thin	-
Vair = 220 m/s:				
avg. fiber dia.(microns)-	5.6	7.1	3.9	4.2
shot intensity avg. -	19.7	6.3	5.2	9.7
shot rating -	1.0	-	0.5	-
web sample thickness -	thin	medium	thin	thick
Vair = 327 m/s:				
avg. fiber dia.(microns)-	3.9	5.1	2.7	3.0
shot intensity avg. -	7.1	3.8	3.1	5.5
shot rating -	0.5	-	0.5	-
web sample thickness -	thin	thick	thin	thick

Table 6.8: Results obtained for the repeatability of various 800 MFR polymers, where the thick web samples were averaged. $T_{air} = T_{poly} = 550^{\circ}\text{F}$.

Throughput	800-B	800-B	800-B	800-B	800-F	800-F
0.8 gpm/hole	run 1	run 2	run 3	run 4	run 1	run 2
Vair = 143 m/s:						
avg. fiber dia.(microns)-	8.0	3.7	4.9	4.4	6.3	10.0
shot intensity avg. -	26.1	15.5	9.4	11.0	25.9	18.7
shot rating -	1.5	-	2.5	3.0	1.5	-
web sample thickness -	thin	medium	medium	thin	thin	medium
Vair = 220 m/s:						
avg. fiber dia.(microns)-	4.0	4.7	2.1	1.9	3.8	4.9
shot intensity avg. -	6.0	7.6	2.6	3.0	7.6	8.8
shot rating -	1.0	-	2.0	2.5	0.5	-
web sample thickness -	thin	thick	thick	thick	thin	thick
Vair = 327 m/s:						
avg. fiber dia.(microns)-	2.1	2.4	2.2	1.7	2.9	2.9
shot intensity avg. -	1.6	2.2	1.7	1.6	4.6	5.4
shot rating -	0.5	-	1.5	1.0	0.5	-
web sample thickness -	thin	thick	thick	thick	thin	thick
1.2 gpm/hole						
Vair = 143 m/s:						
avg. fiber dia.(microns)-	7.6	5.4	5.9	6.1	11.4	14.5
shot intensity avg. -	25.3	20.5	9.9	9.5	17.3	9.2
shot rating -	3.0	-	4.5	5.0	3.0	-
web sample thickness -	thin	medium	thin	thin	thin	thin
Vair = 220 m/s:						
avg. fiber dia.(microns)-	4.8	4.0	5.4	2.9	5.1	7.2
shot intensity avg. -	15.0	12.3	3.1	4.3	12.1	11.3
shot rating -	1.5	-	3.0	3.5	2.0	-
web sample thickness -	thin	thick	thick	thick	thin	medium
Vair = 327 m/s:						
avg. fiber dia.(microns)-	2.6	2.3	2.5	2.7	3.8	3.9
shot intensity avg. -	3.8	1.9	1.9	2.3	7.4	3.8
shot rating -	0.5	-	1.5	2.5	1.0	-
web sample thickness -	thin	thick	thick	thick	thin	medium

Table 6.9: Results obtained for the repeatability of various 1000 MFR polymers, where the thick web samples were averaged. $T_{air} = T_{poly} = 450\text{ }^{\circ}\text{F}$.

Throughput	1000-A	1000-A	1000-B	1000-B
0.8 gpm/hole	run 1	run 2	run 1	run 2
Vair = 143 m/s:				
avg. fiber dia.(microns)-	-	6.6	-	8.5
shot intensity avg. -	-	8.2	-	5.6
shot rating -	-	-	-	-
web sample thickness -	-	medium	-	thin
Vair = 220 m/s:				
avg. fiber dia.(microns)-	3.5	5.0	4.2	4.2
shot intensity avg. -	4.5	2.6	4.2	2.9
shot rating -	0.5	-	0.5	-
web sample thickness -	thin	medium	thin	medium
Vair = 327 m/s:				
avg. fiber dia.(microns)-	2.7	2.4	2.2	2.8
shot intensity avg. -	1.9	2.3	2.9	1.6
shot rating -	0.5	-	0.5	-
web sample thickness -	thin	thick	thin	thick
1.2 gpm/hole				
Vair = 143 m/s:				
avg. fiber dia.(microns)-	8.2	9.8	12.9	12.1
shot intensity avg. -	23.2	11.3	24.4	5.3
shot rating -	2.0	-	1.5	-
web sample thickness -	thin	medium	thin	thin
Vair = 220 m/s:				
avg. fiber dia.(microns)-	5.3	4.6	5.8	5.4
shot intensity avg. -	10.9	4.4	11.8	5.0
shot rating -	0.5	-	0.5	-
web sample thickness -	thin	thick	thin	medium
Vair = 327 m/s:				
avg. fiber dia.(microns)-	4.1	3.0	2.9	3.2
shot intensity avg. -	4.2	1.2	0.8	1.9
shot rating -	0.5	-	0.5	-
web sample thickness -	thin	thick	thin	thick

polymers, respectively. These tables present results using the averaging of shot intensity values for thick samples. The case of adding shot intensity can easily be calculated by multiplying the thick sample average shot intensity value by 2. Upon examination of these tables, the repeatability of the average fiber diameters was found to be within the uncertainty value of ± 1.25 microns for all three MFR cases. Tables 6.7 through 6.9 show that a particular polymer can be tested at different times (at the same processing conditions) with the confidence that similar results will be obtained each time. Such comments cannot be made for the shot intensity values however. When compared to each other for the same polymer, these values were in some cases dramatically different and in other cases fairly close to one another. For this reason, a conclusion concerning the reproducibility of shot intensity values was not able to be made with confidence. However, it was concluded that these differences were due in part to the wide variety of web thickness of the samples used. It was found that the thicker the web samples were, the harder it was for the microscope light to penetrate the sample; thus, resulting in inaccurate shot intensity values. Therefore, it was determined that webs of less than 0.6 ounces per square yard should be collected and used to confidently obtain shot intensity measurements. Finally, since only one polymer (800-B) had shot rating values, no repeatability conclusion for this technique was made. However it should be noted that for 800-B runs 3 and 4, the shot rating values appeared to be reproducible.

Investigation of Changes in Polymer Temperature

This section describes the results obtained from web samples collected over a range of polymer temperatures. As was stated in Chapter III, the range of temperatures examined was between 450 and 364 degrees Fahrenheit. During the entire investigation, the air jet temperature was kept at a constant 400 degrees Fahrenheit, and the polymer throughput was set at a constant 0.8 grams/minute per hole.

Shot Intensity

As was mentioned in the last section, complications arise when trying to perform the shot intensity technique on a web sample that is greater than 1 ounce per square yard. Therefore, for this study, web samples were collected at the recommended size of 0.6 ounces per square yard. Figure 6.1 is a graph of shot intensity versus air exit velocity for polymer temperatures between 450 and 364 degrees Fahrenheit. The figure shows the shot intensity value decreasing with increasing air velocity. A trend identical to this was observed during the investigation of various polymers earlier in this chapter. Figure 6.1 also shows the shot intensity value decreasing with decreasing polymer temperature. This could suggest that as the polymer fibers are extruded at cooler temperatures, they will tend to solidify sooner, thus decreasing the chance of "fusion" between any two fibers that may collide or "touch" close to the die exit plane.

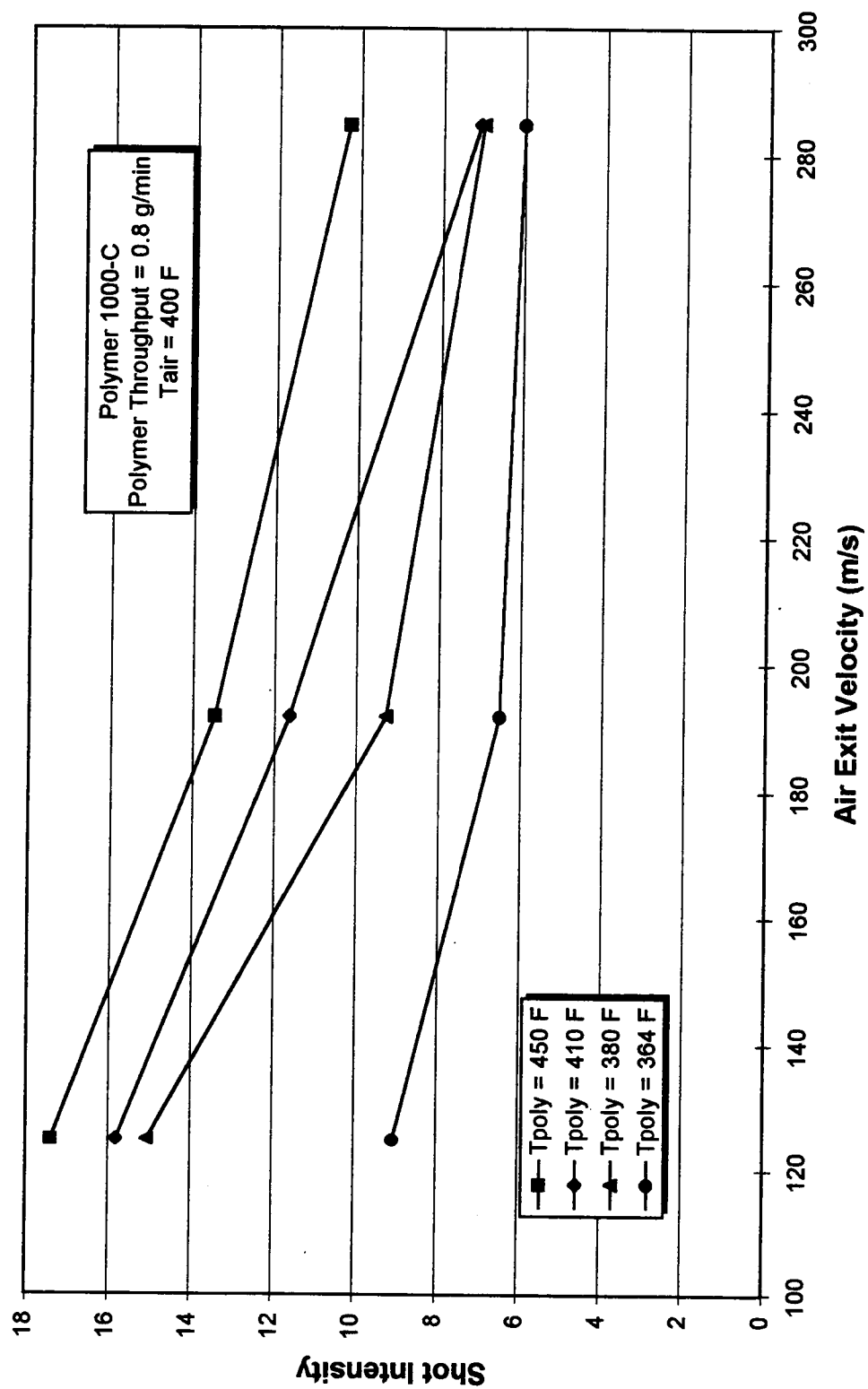


Figure 6.1: Effect of polymer temperature on shot intensity.

Fiber Diameter

The effect the change in polymer temperature had on the average fiber diameters of the samples collected is shown in Figures 6.2 and 6.3. Both figures show the average fiber diameter decreasing with increased air velocity and increased polymer temperature. This decreasing effect is the greatest at low air velocities. These results are similar to those found by Spencer [14]. The decrease in fiber diameter at high polymer temperatures can be attributed to the amount of attenuation time the fiber has before reaching its solidification temperature and the percentage of die swell at the exit of the die orifice holes. Die swell is due to the viscoelastic effects of the polypropylene resin. It is defined as the ratio of diameter of the extrudate to the diameter of the die orifice hole. Therefore, the higher the polymer temperature is, the longer the attenuation time and the smaller the percentage of die swell [13] will be.

Investigation of Fiber Dynamics and Air Flowfield Characteristics

The following sections describe the results obtained using stop motion photography, high speed video, and nozzle air velocity measurements to examine how the extruded fiber and air flowfield behaved upon leaving the die test section.

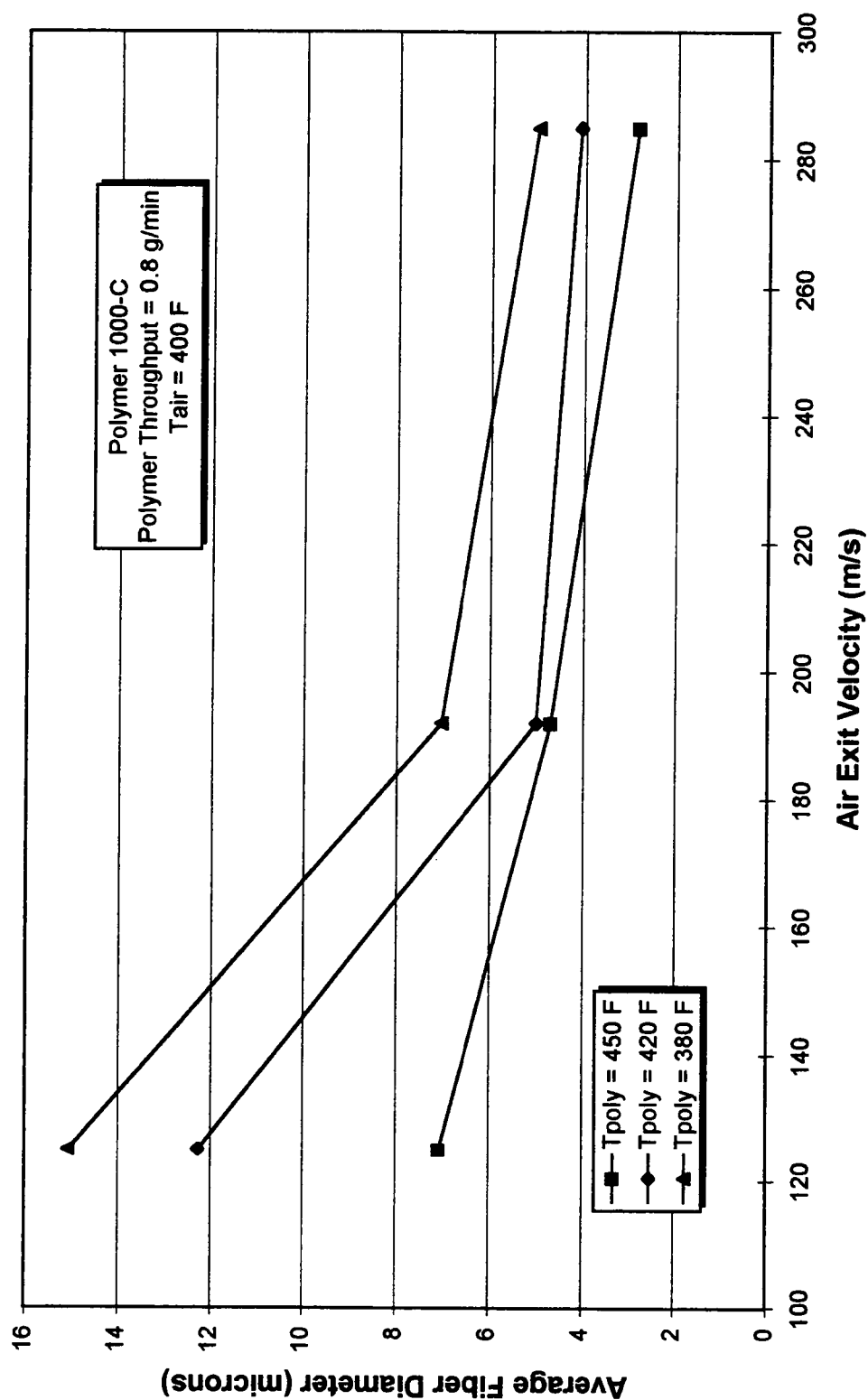


Figure 6.2: Effect of polymer temperature on average fiber diameter, for polymer temperatures between 450 and 380 degrees Fahrenheit.

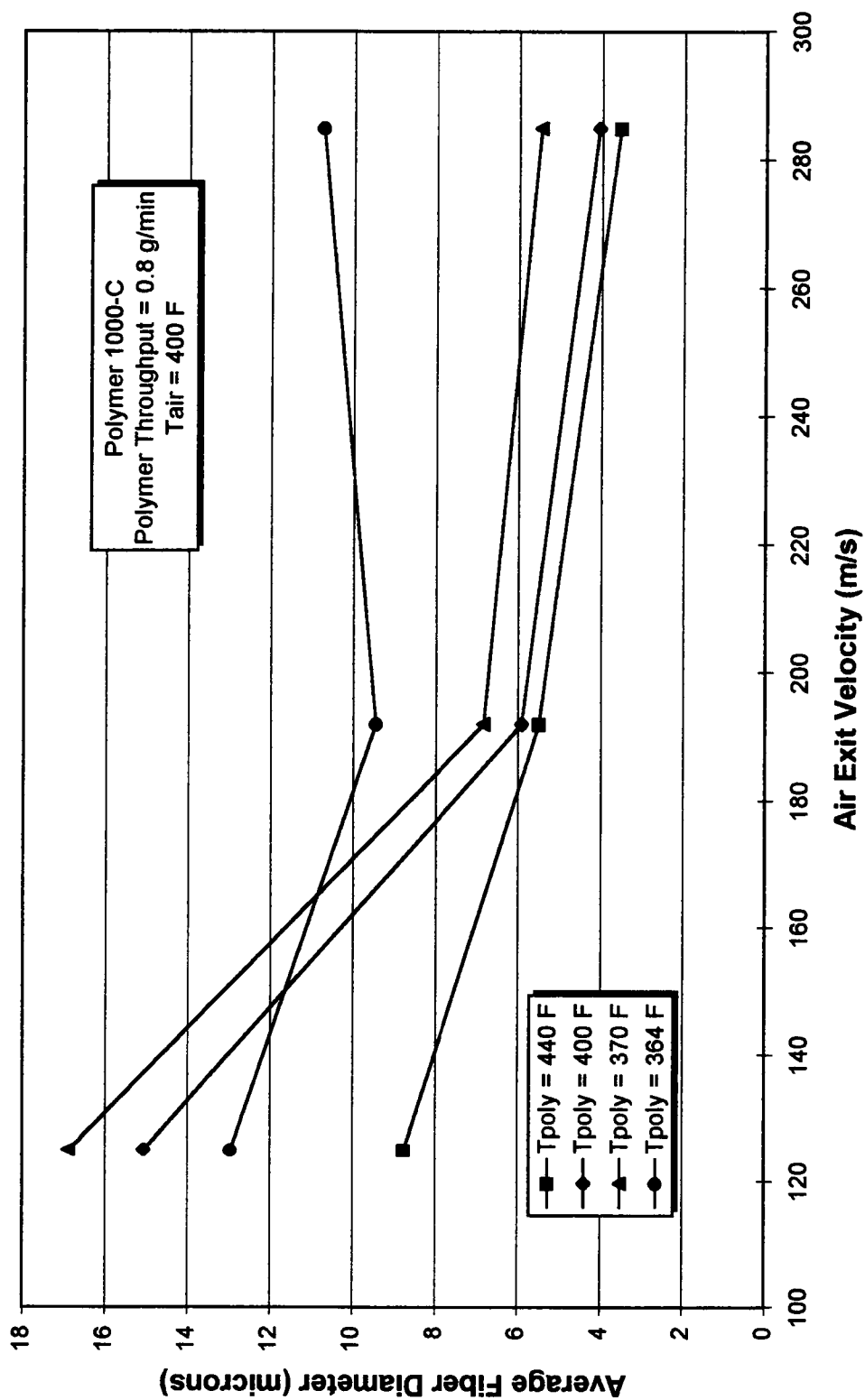


Figure 6.3: Effect of polymer temperature on average fiber diameter, for polymer temperatures between 440 and 364 degrees Fahrenheit.

Investigation of Fiber Motion in a Single Plane

As was described in Chapter IV, both the multi-hole and single hole dies were used to examine fiber dynamics leaving the die. Stop motion photography using a Nikon 35mm camera was used to obtain the results for the multi-hole investigation and a high speed video camera was used to obtain results for the single hole investigation.

Multi-Hole Stop Motion Photography

Figures 6.4 through 6.7 show some of the typical pictures that were obtained using the 35mm camera. The pictures shown in Figures 6.4 and 6.5 were obtained at a polymer throughput of 0.8 grams/minute per hole and air exit velocities of 143 and 330 meters/second, respectively. Upon examination of these figures, two important fiber dynamic results become apparent. The first is shown in Figure 6.4 where the air velocity at the nozzle exit was the lowest. Examining the fibers close to the die exit plane, an interaction or collision of fibers can be seen at distances as close as 1/4 inch from the die exit. Since, the polymer fibers are typically still molten at such close distances, these collisions appear to result in the fusing of two adjacent fibers, thus causing them to join into a single fiber of larger cross-section. This "touching" phenomenon, however, seemed to disappear as the air velocity was increased to 330 meters/second as shown in Figure 6.5. The increased air velocity tended to establish a more uniform flow of the polymer fibers, thus, decreasing the chance for fibers to interact with one another close to the die exit plane. Figures 6.6 and 6.7 show polymer fibers being extruded at a throughput of 1.2

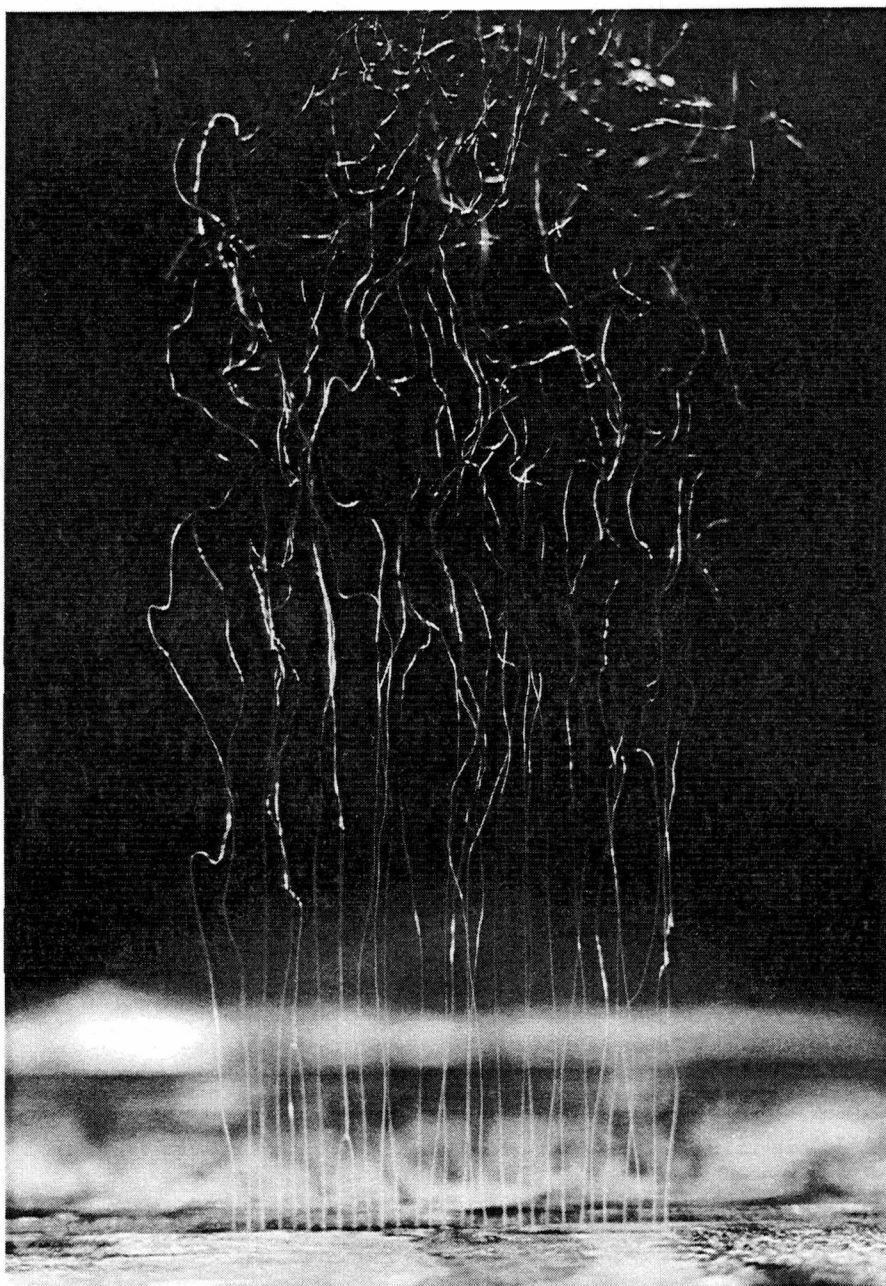


Figure 6.4: Stop Motion photograph of multi-hole die with 0.8 ghm throughput and 143 m/s air velocity.

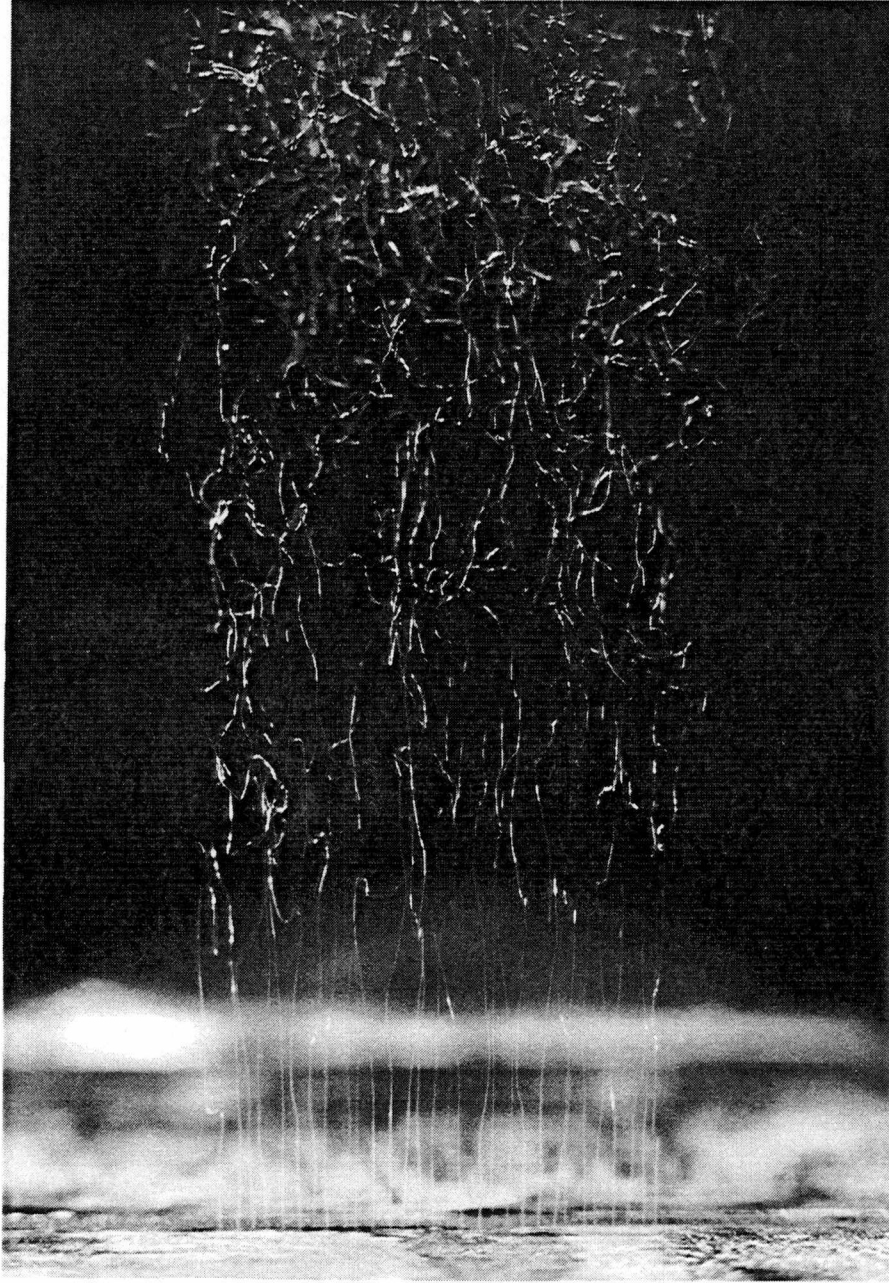


Figure 6.5: Stop Motion photograph of multi-hole die with 0.8 ghm throughput and 330 m/s air velocity.

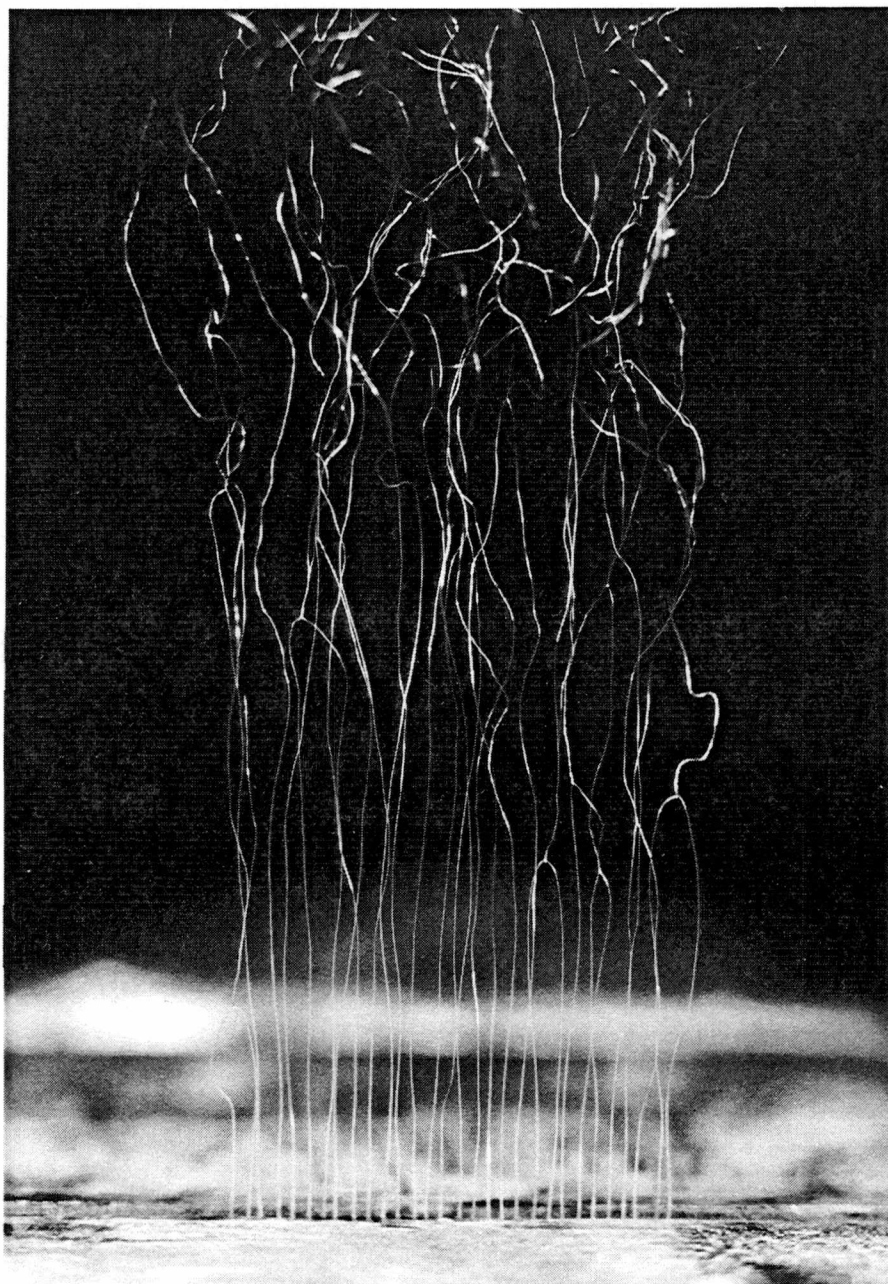


Figure 6.6: Stop Motion photograph of multi-hole die with 1.2 ghm throughput and 143 m/s air velocity.

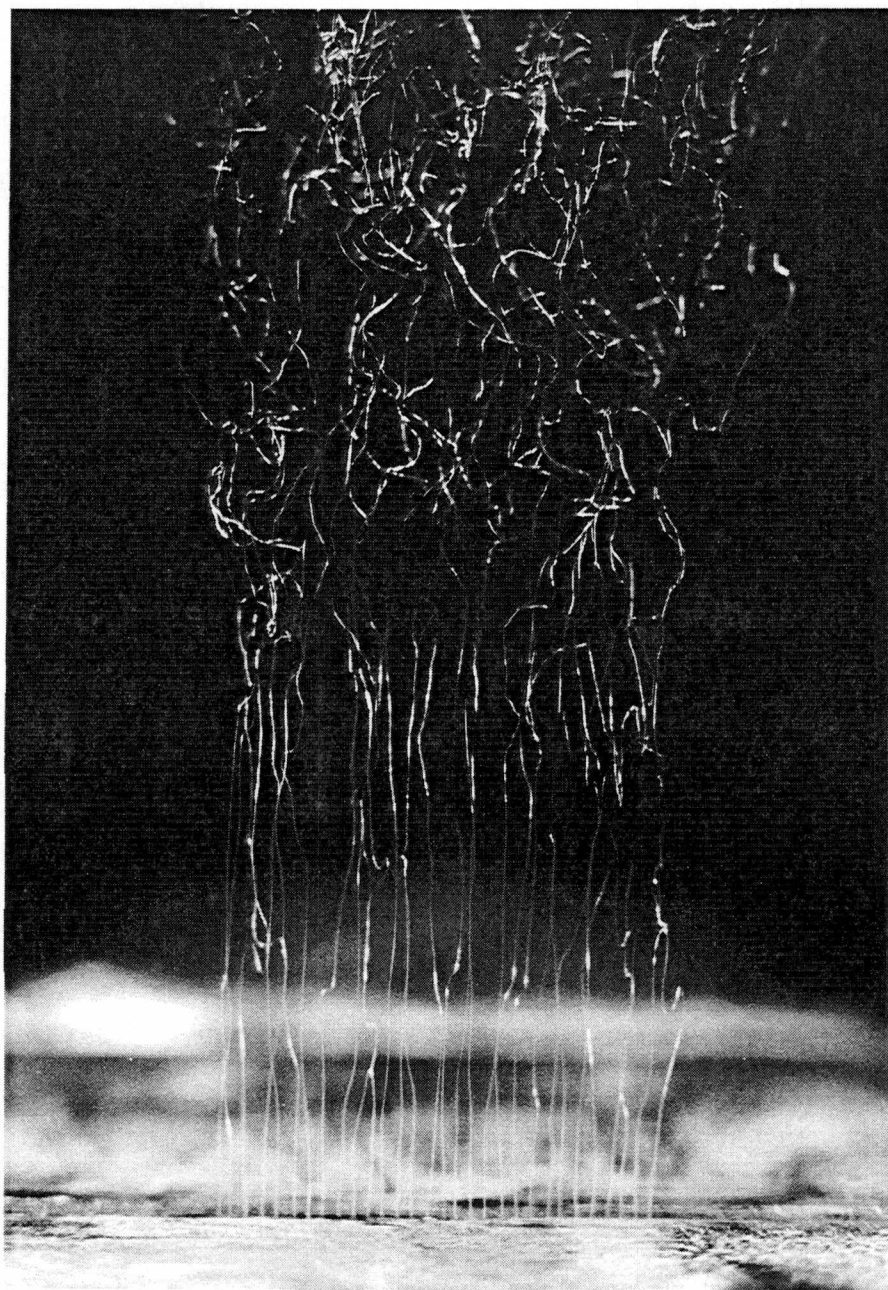


Figure 6.7: Stop motion photograph of multi-hole die with 1.2 ghm throughput and 270 m/s air velocity.

grams/minute per hole at air velocities of 143 and 270 meters/second. Results similar to those found for the lower throughput were observed for this case as well. Again, at the low air velocities, the fibers shown in Figure 6.6 tended to collide and fuse together at distances close to the die exit. The fused fibers would then travel downstream as a single larger fiber. Similar to Figure 6.5, as the air velocity was increased in Figure 6.7, the fibers appeared to exhibit fewer fiber-to-fiber interactions. Therefore, the results of this investigation show that extruded fibers may collide at distances close to the die exit plane. Since these distances are at locations where the fibers have not begun to solidify, the fibers will fuse together into a single filament with a larger cross-section. By increasing the air velocity, it was shown that these collisions would decrease. This increase in air velocity tended to setup a more uniform polymer flowfield resulting in fewer collisions. Since the solidification temperature of the polymer fibers determines whether or not the fibers will fuse upon collision, another contribution of an increased air velocity flow is that of cooling. Higher air velocities will increase the amount of convective cooling the fiber experiences upon leaving the die. This increased cooling would lead to shorter solidification times. As was mentioned in the previous section concerning the effects of polymer temperature, if the fibers are already solidified upon collision, they will not to fuse together.

Single Fiber Plane Motion

Having observed the fiber collisions using the multi-hole die, the single hole die was then used to observe how far a single fiber would traverse across a plane perpendicular to the die exit plane. As described in Chapter IV, four locations at distances of 0.159, 0.292, 0.422, and 0.55 inches from the die exit plane were examined. Both 0.8 and 1.2 grams/minute per hole throughput were used at air velocities between 121 and 330 meters/second. Figures 6.8 through 6.12 show the results obtained for the 0.8 grams/minute case. In these figures, the lateral displacement can be seen traversing lateral distances as wide as 0.056 inches, with the greatest occurring at distances farthest from the die exit plane. The larger lateral displacements at the farthest locations can be attributed to the increased flapping motion fibers experience as the distance from the die exit increases. Figures 6.13 through 6.15 show similar results for the 1.2 grams/minute case. The most important finding of this study was the determination that a single fiber will traverse back and forth distances as large as 0.056 inches, which is greater than the die orifice hole spacing. Therefore, if each extruded filament is traversing 0.056 inches, then for a 30 hole die whose hole-to-hole centerline spacing would be 0.033 inches, there is no doubt that the probability of fiber-to-fiber interactions is high. As the air velocity was increased, the fiber traversing distances became wider. This observation was unexpected since the multi-hole die exhibited more uniform fiber flow as the air velocity was increased. This suggests that if the fibers do collide close to the die, the increased air velocity cools the fibers to temperatures at or below the solidification temperature, thus

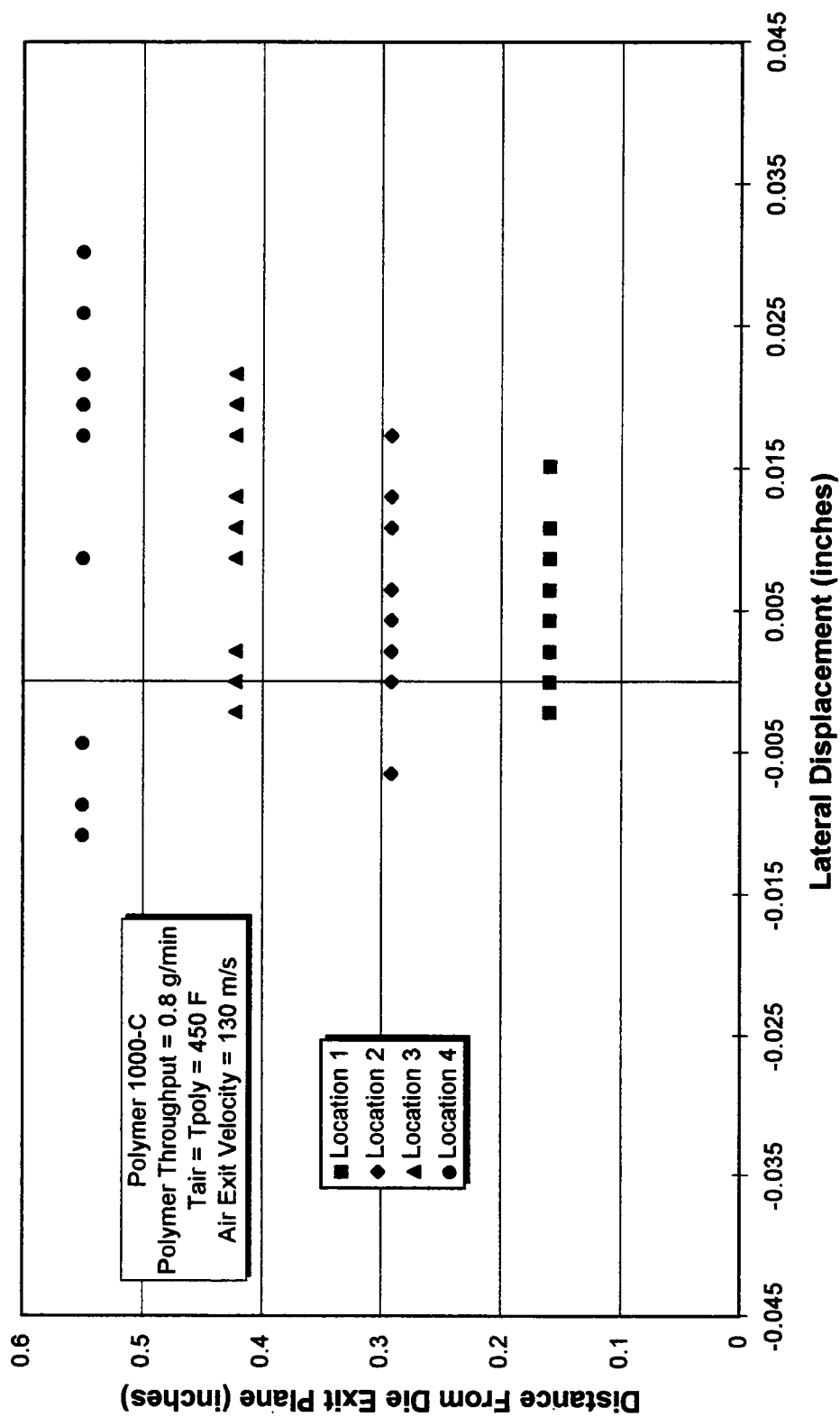


Figure 6.8: Lateral displacement of a single fiber at polymer throughput of 0.8 g/min and air exit velocity of 130 m/s.

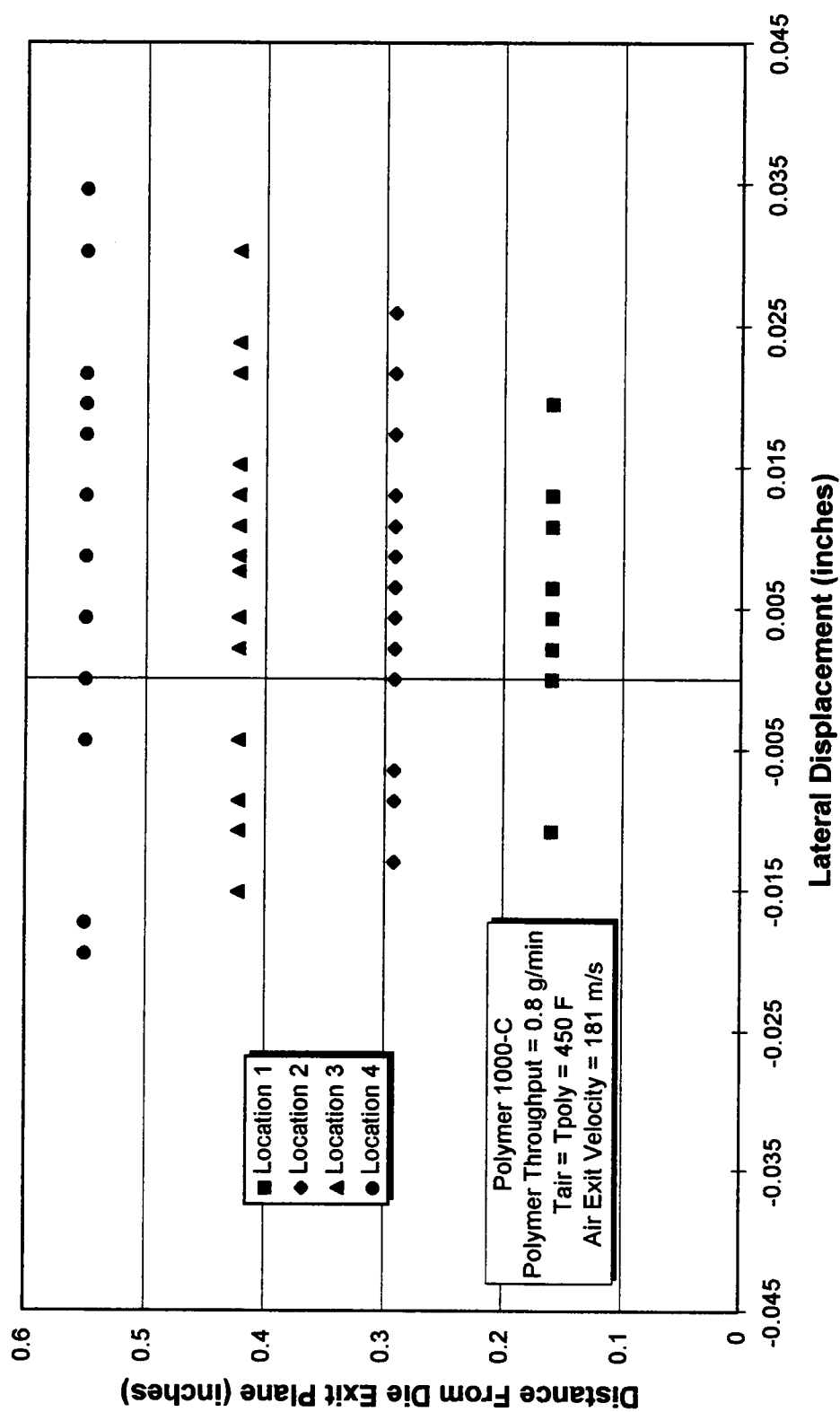


Figure 6.9: Lateral displacement of a single fiber at polymer throughput of 0.8 g/min and air exit velocity of 181 m/s.

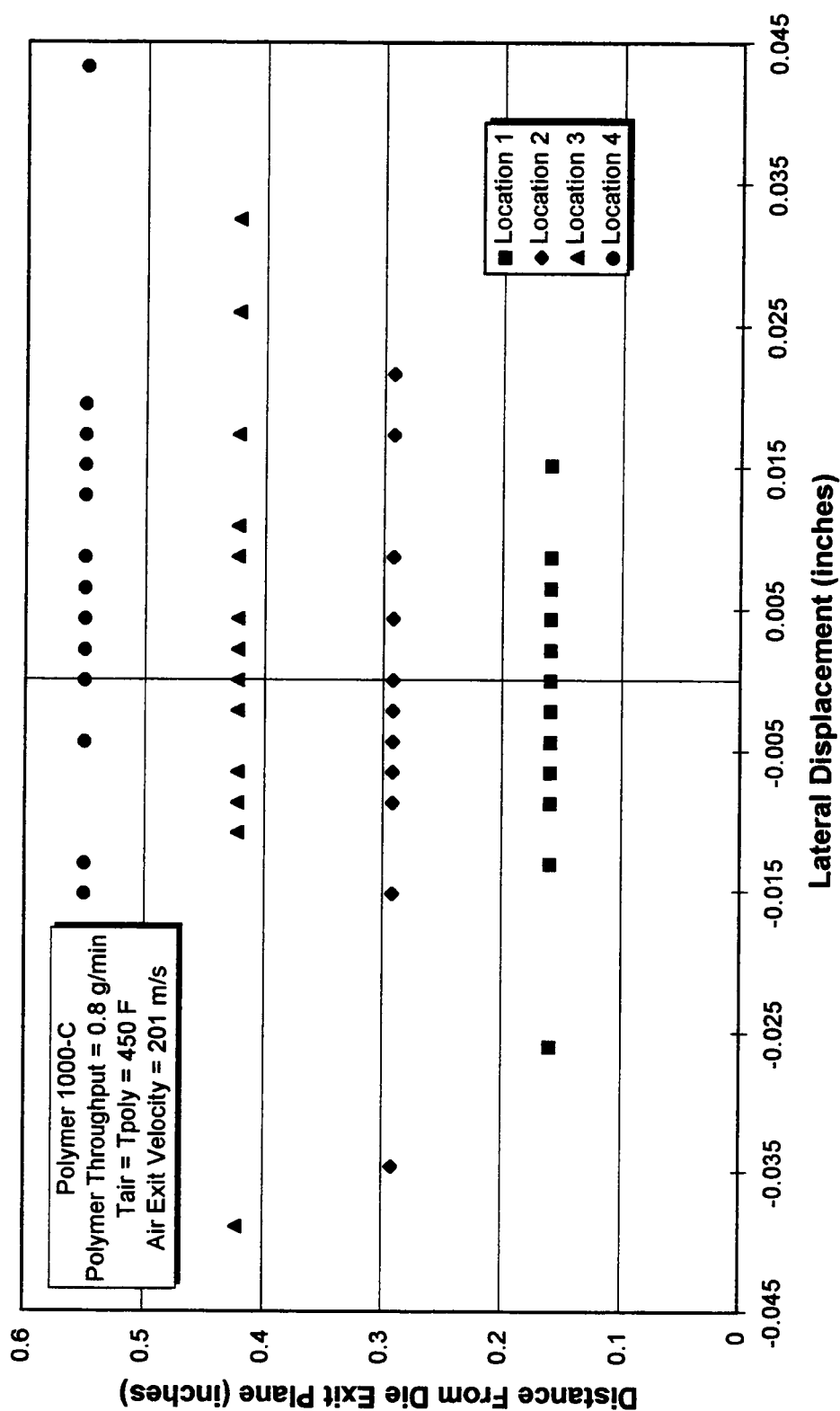


Figure 6.10: Lateral displacement of a single fiber at polymer throughput of 0.8 g/min and air exit velocity of 201 m/s.

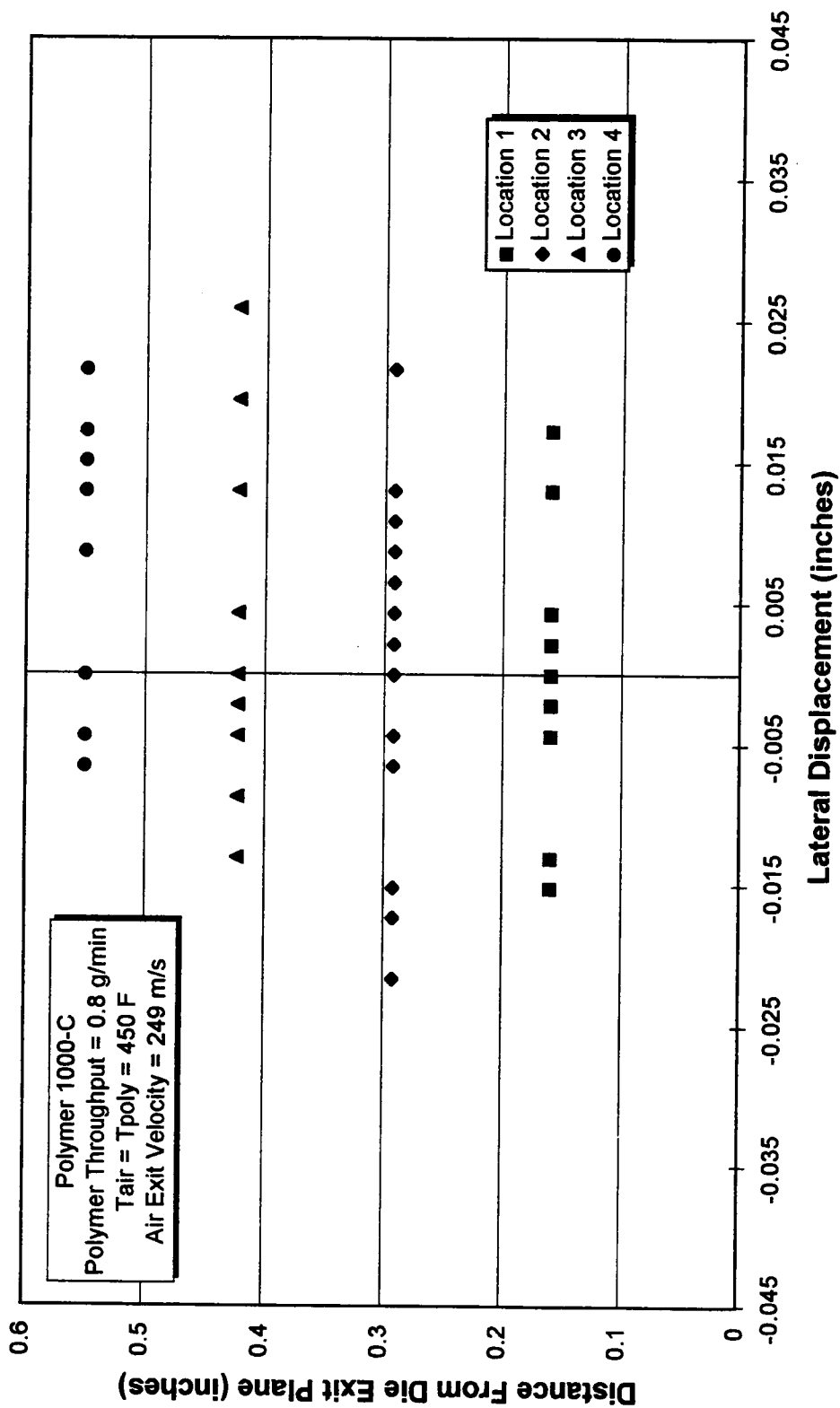


Figure 6.11: Lateral displacement of a single fiber at polymer throughput of 0.8 g/min and air exit velocity of 249 m/s.

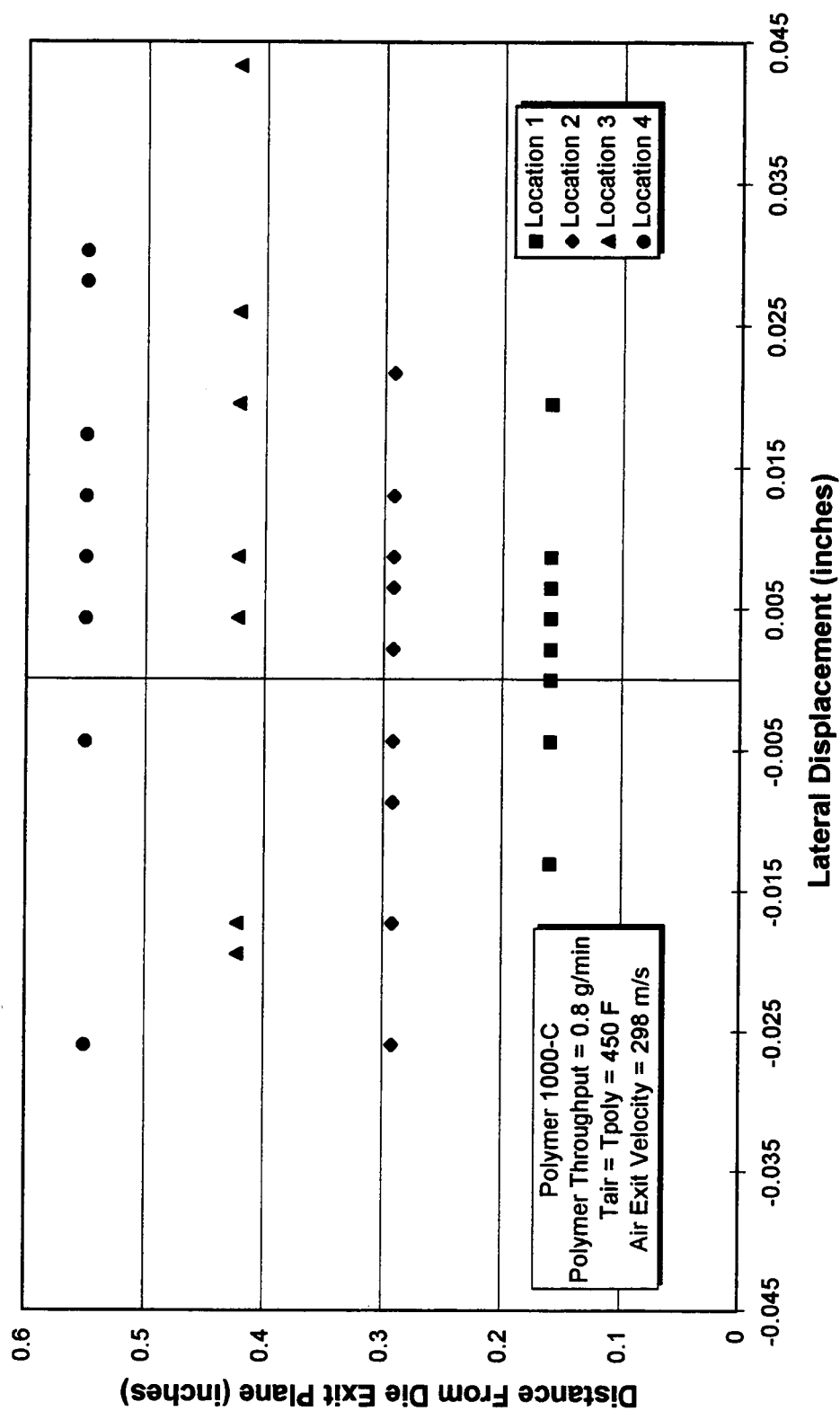


Figure 6.12: Lateral displacement of a single fiber at polymer throughput of 0.8 g/min and air exit velocity of 298 m/s.

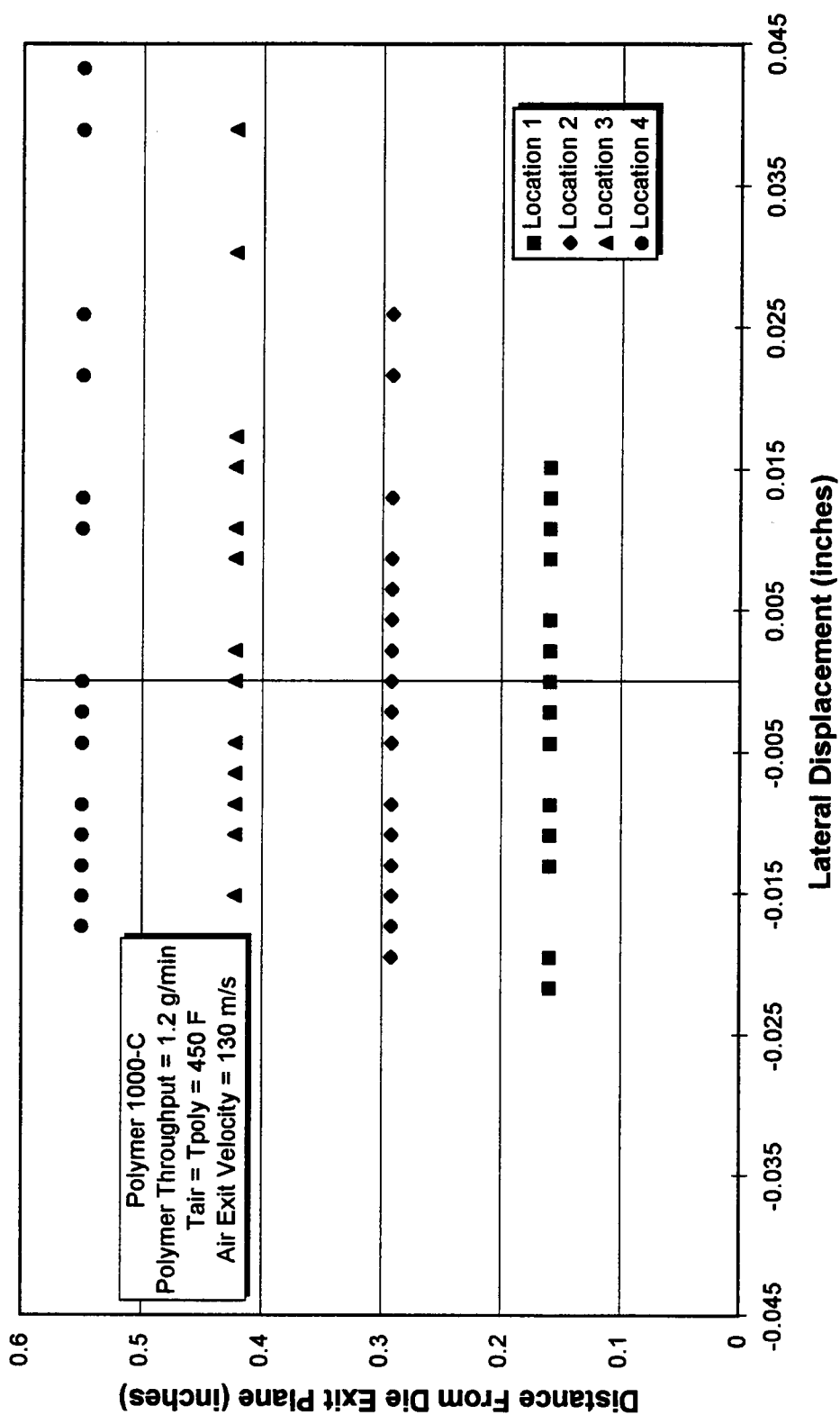


Figure 6.13: Lateral displacement of a single fiber at polymer throughput of 1.2 g/min and air exit velocity of 130 m/s.

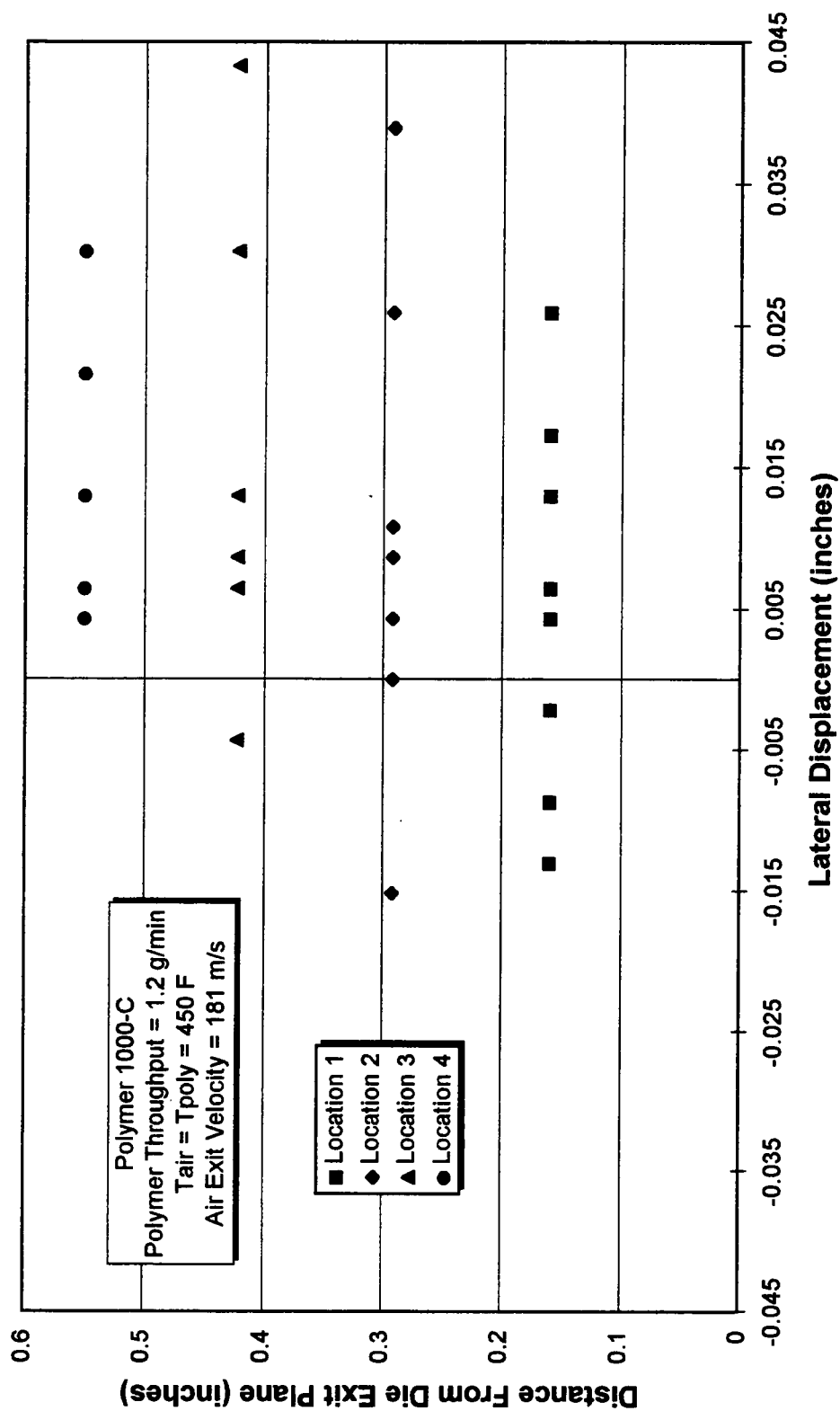


Figure 6.14: Lateral displacement of a single fiber at polymer throughput of 1.2 g/min and air exit velocity of 181 m/s.

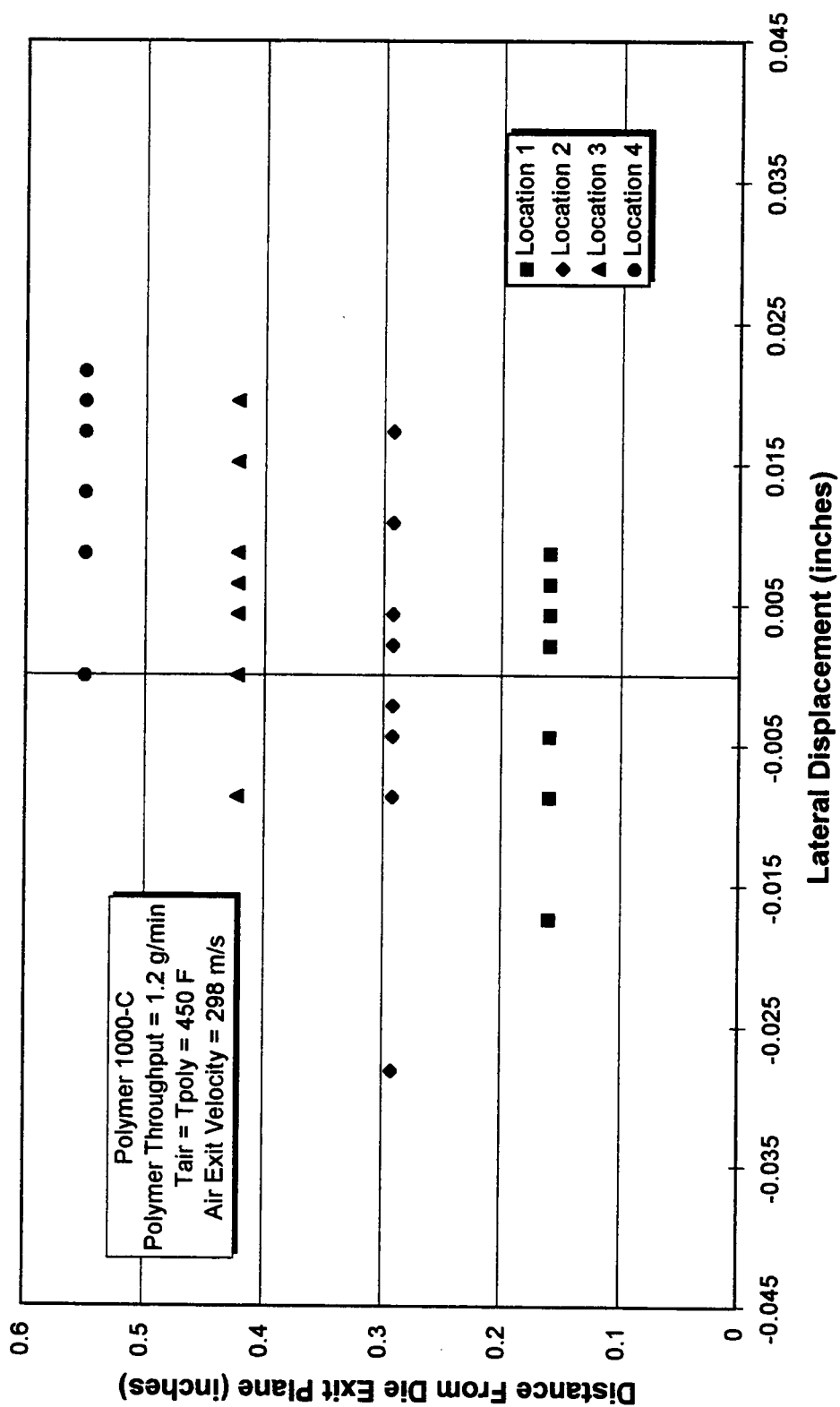


Figure 6.15: Lateral displacement of a single fiber at polymer throughput of 1.2 g/min and air exit velocity of 298 m/s.

decreasing the amount of filament fusion.

The results obtained for the previous two investigations suggests that rather than shot being produced by the breaking of fibers and "snapping" back of the fiber ends, as described by other investigators [1,10, and 11], the principal shot producing mechanism is the collision of molten fibers at distances close to the die exit plane. During this investigation, two types of shot particles have been observed to occur randomly within the web samples. The first type resembles a film spot which showed signs of melting the adjacent fibers. This type of shot would be caused by fused fibers not reaching their solidification temperature, thus, being molten upon striking the collector. The second form observed was found to show no signs of web melting and were not significantly attenuated. This form is due to fused fibers reaching their solidification temperatures early enough to avoid significant draw down, before arriving at the collector.

Investigation of a Converging Nozzle Flowfield

The following sections describe the results obtained using a 90 degree pitot tube to measure centerline velocities of the jet flowfield attributed to the converging nozzle melt blown configuration. As described in Chapter IV, measuring orifice h_m 's of 2, 5, and 12 inches of water were the three flow conditions investigated.

Measuring Orifice Delta Pressure of 2 inches of water

In Figure 6.16, a plot of the velocity measured across the entire die face at a distance of 0.25 inches from the die exit plane is shown. This velocity profile was found to be a constant 81.5 meters/second for the entire length. The value obtained from Equation 2.4 was 78 meters/second; therefore, the velocity measured was within ± 4 meters/second of the velocity calculated. Due to the large amount of time required to take measurements in the x-direction, across the entire die exit plane, initial measurements were made to determine if the flowfield was symmetrical. These measurements indicated that the flowfield was symmetrical, thus, only half of the jet flowfield was investigated while examining the axial velocities in the x-direction. The centerline velocity profile (at $x = 2$ inches) in the z-direction is shown in Figure 6.17. This figure shows the centerline air velocity decreasing from 81.5 meters/second, at a location 0.25 inches from the die exit plane, to 23 meters/second at a distance of 16 inches (the typical DCD distance) from the die exit plane. Figures 6.18 and 6.19 show contour plots of centerline velocity profiles for traverses across the die exit plane in both x- and y-directions. Examining these figures, a resemblance to the classical free jet flowfield can be seen. This resemblance was noted by Haynes [18] during his investigation of air drag on monofilament fibers.

Measuring Orifice Delta Pressure of 5 inches of water

A plot of the centerline velocity traverse measurement (in the x-direction), for a measuring orifice value of $h_m = 5$ inches of H₂O, 0.25 inches from the die exit plane is

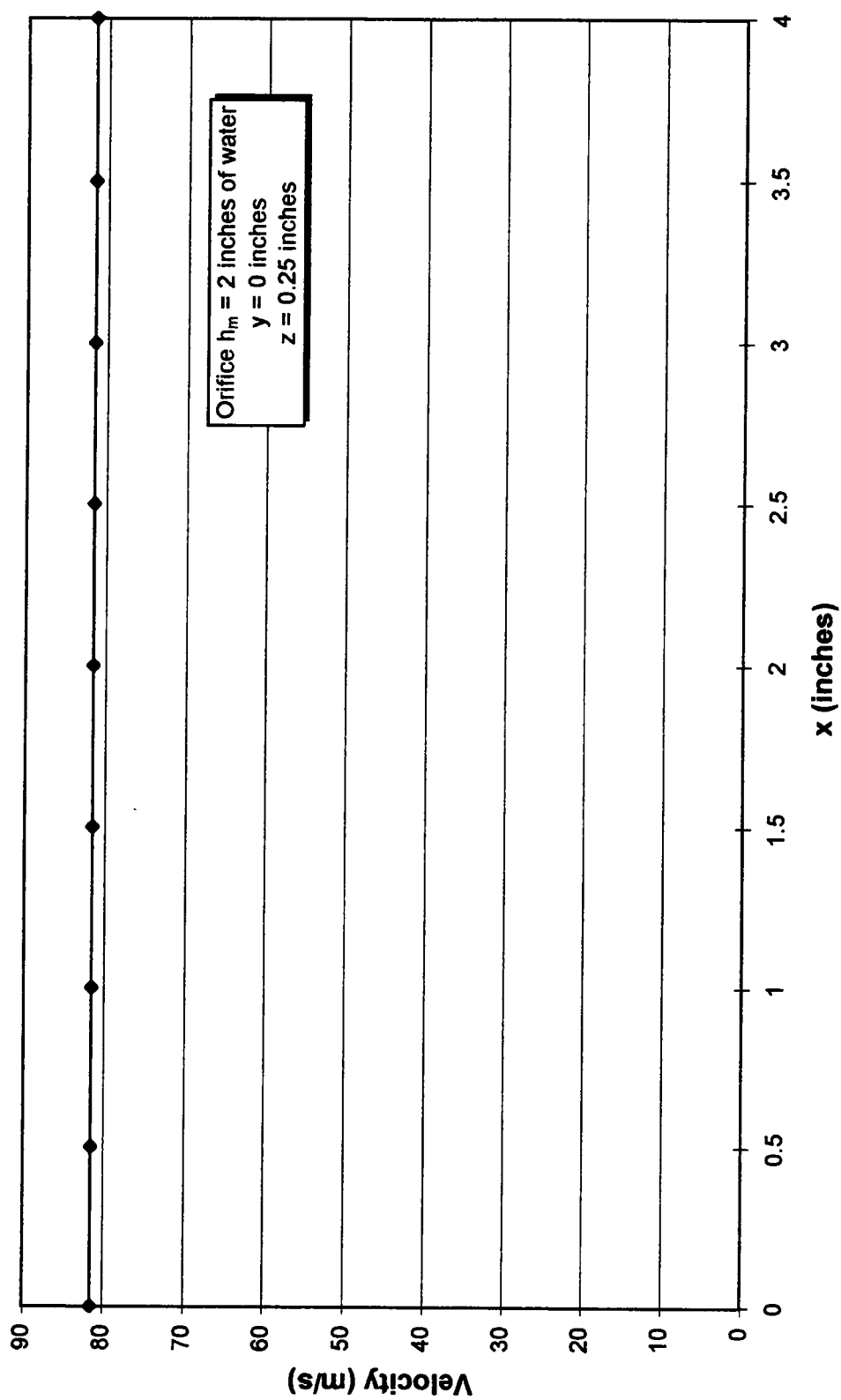


Figure 6.16: Centerline velocity profile measured in the x - direction at a location of $z = 0.25$ inches and $y = 0$ inches. Measuring orifice delta pressure of 2 inches of water.

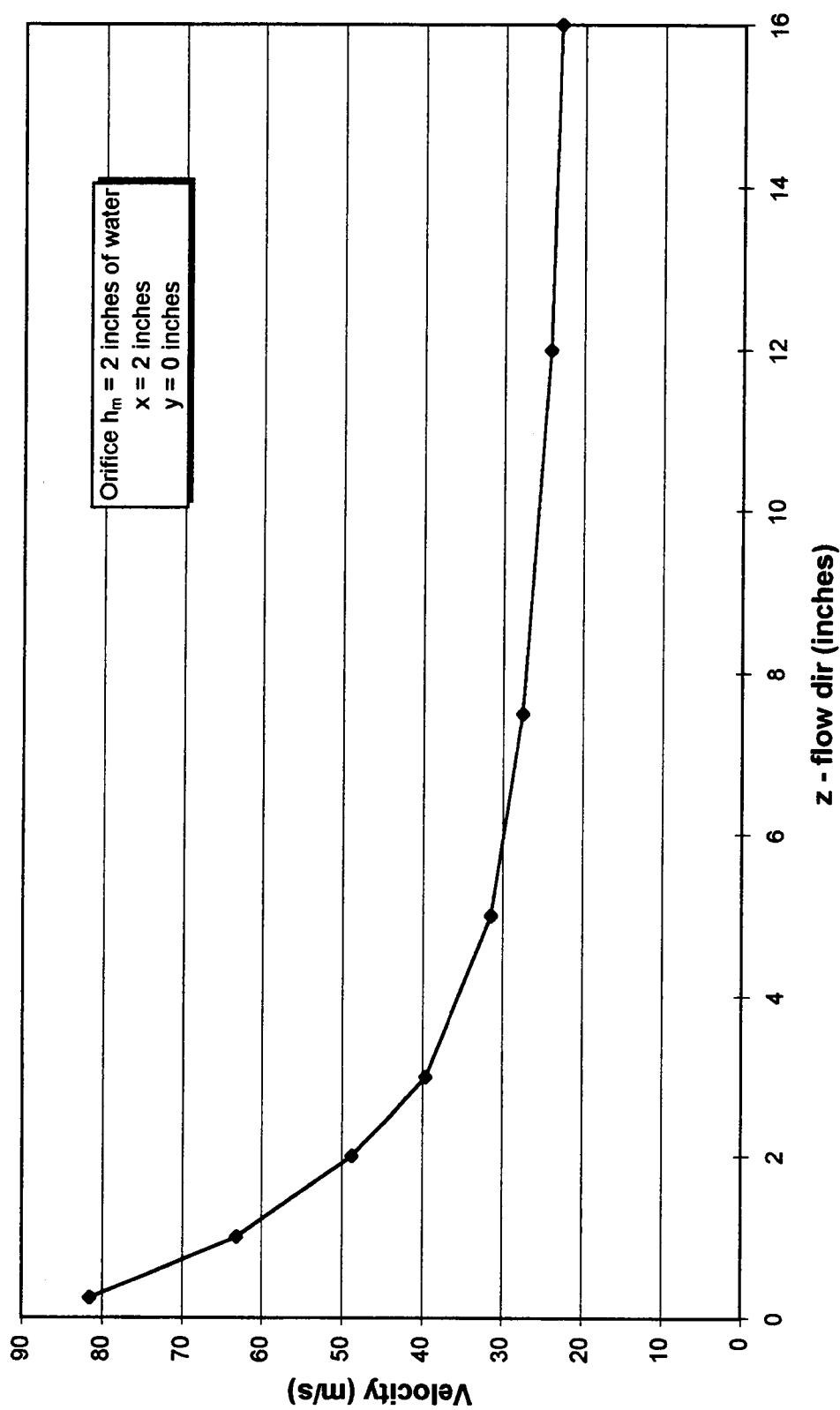


Figure 6.17: Centerline velocity profile measured in the z - direction at a location of $x = 2$ inches and $y = 0$ inches. Measuring orifice delta pressure of 2 inches of water.

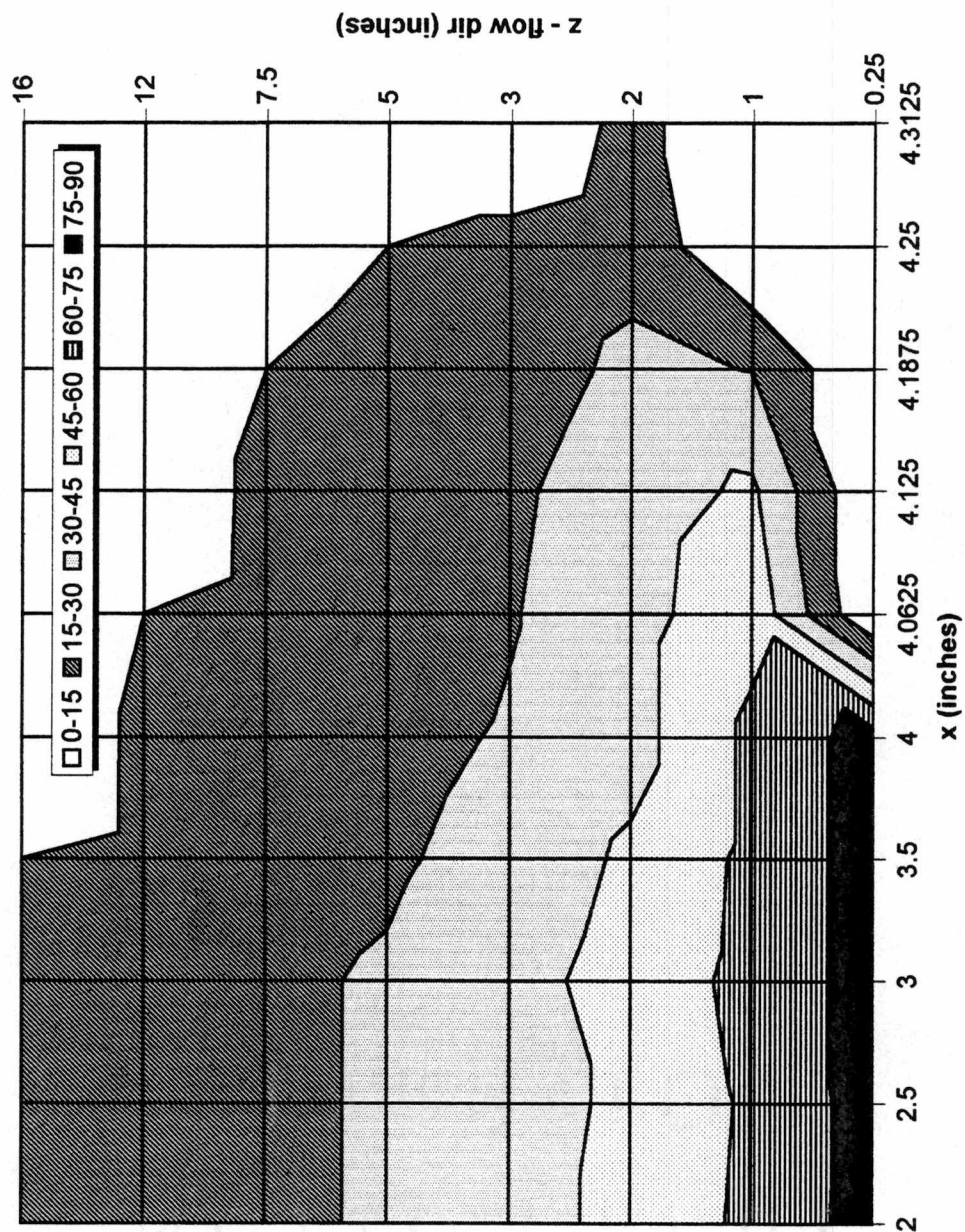


Figure 6.18: Contour plot showing centerline velocities (in m/s) in the x and z plane ($y = 0$ inches). Measuring orifice delta pressure of 2 inches of water.

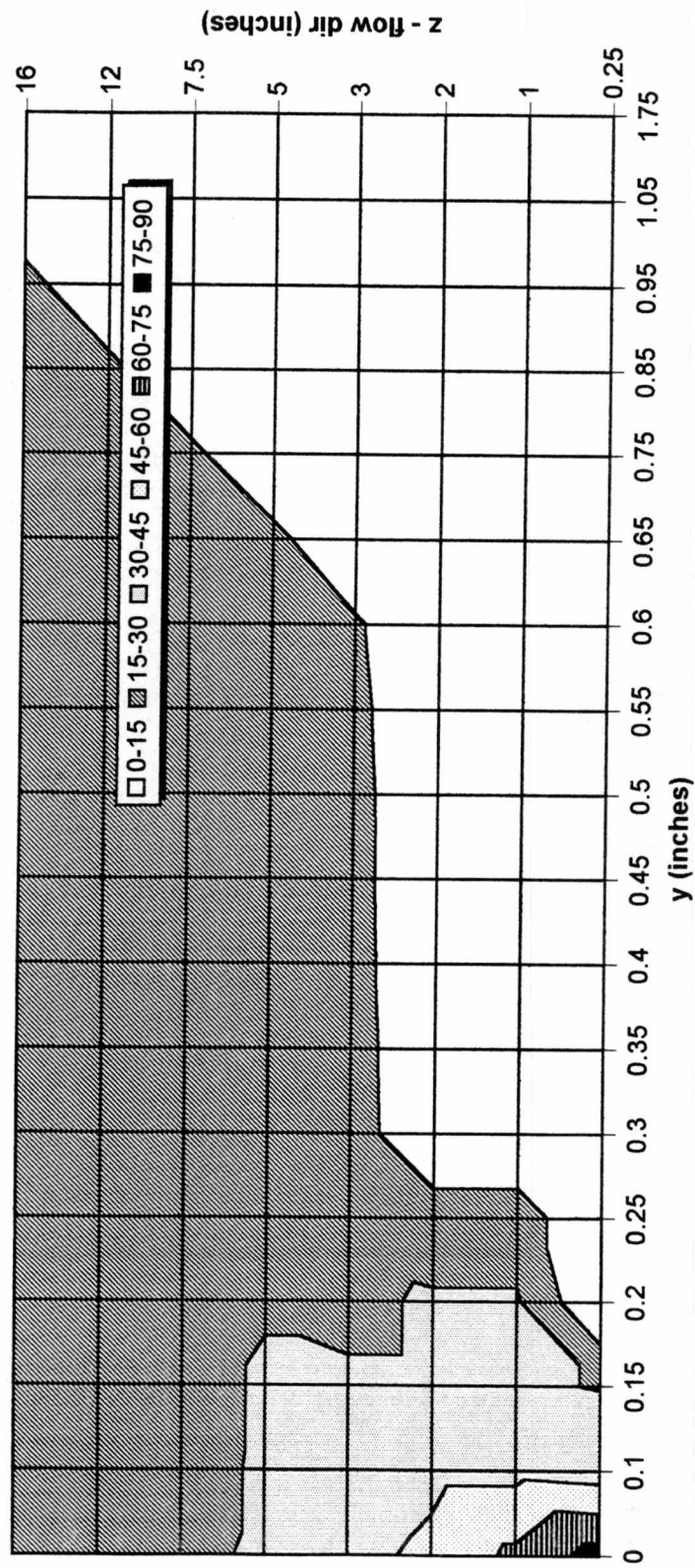


Figure 6.19: Contour plot showing centerline velocities (in m/s) in the y and z plane ($x = 2$ inches). Measuring orifice delta pressure of 2 inches of water.

shown in Figure 6.20. The air velocity measured at this location was found to be a constant 120 meters/second. This value is identical to the value calculated using Equation 2.4. The measured velocity profile in the z-direction is shown in Figure 6.21. This figure shows the air velocity decreasing from a value of 120 meters/second at the die exit plane to 29 meters/second, 16 inches from the die exit plane. As in Figures 6.19 and 6.20, a contour plot of the centerline velocities measured in both the x- and y-directions is shown in Figures 6.22 and 6.23.

Measuring Orifice Delta Pressure of 12 inches of water

The highest velocity measured was that related to a measuring orifice h_m of 12 inches of H₂O. Using Equation 2.4, this corresponds to an exit air velocity of 180 meters/second. A plot of the centerline velocity traverse measurements is shown in Figure 6.24. This graph shows the velocity to be a constant 178 meters/second across the entire die exit plane. This value is 2 meters/second lower than what was calculated using Equation 2.4, but, still within the uncertainty range stated in Chapter IV. The centerline velocity profile in the z-direction is presented in Figure 6.25. This figure shows the air exit velocity (0.25 inches from the die exit) of 178 meters/second dropping, with increasing distance from the exit plane, to a value of 38 meters/second, 16 inches from the die exit. This result was found to be consistent with results presented by Haynes [18]. Figures 6.26 and 6.27 are contour plots showing the traverse centerline velocity profiles in the x- and y-directions.

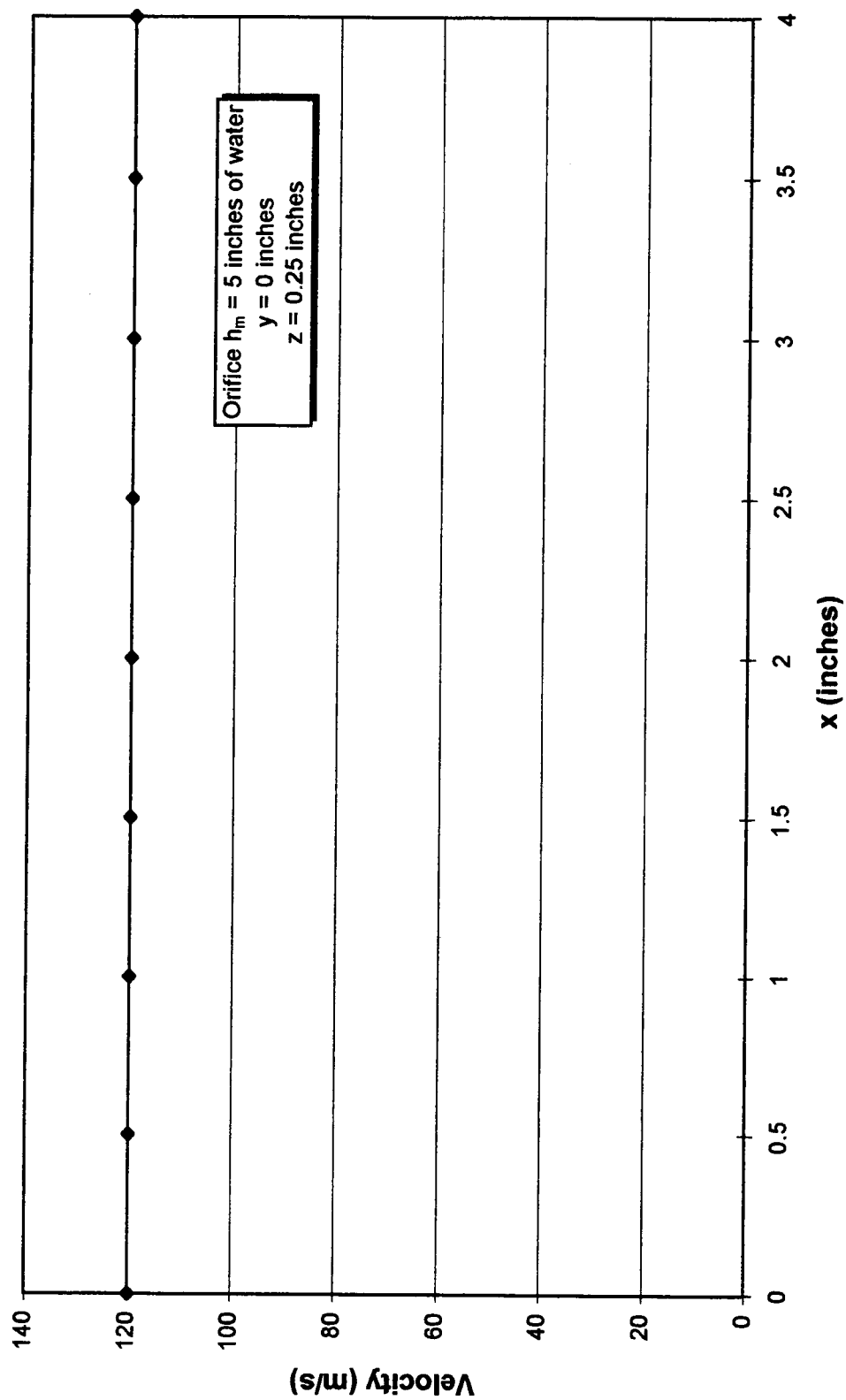


Figure 6.20: Centerline velocity profile measured in the x - direction at a location of $z = 0.25$ inches and $y = 0$ inches. Measuring orifice delta pressure of 5 inches of water.

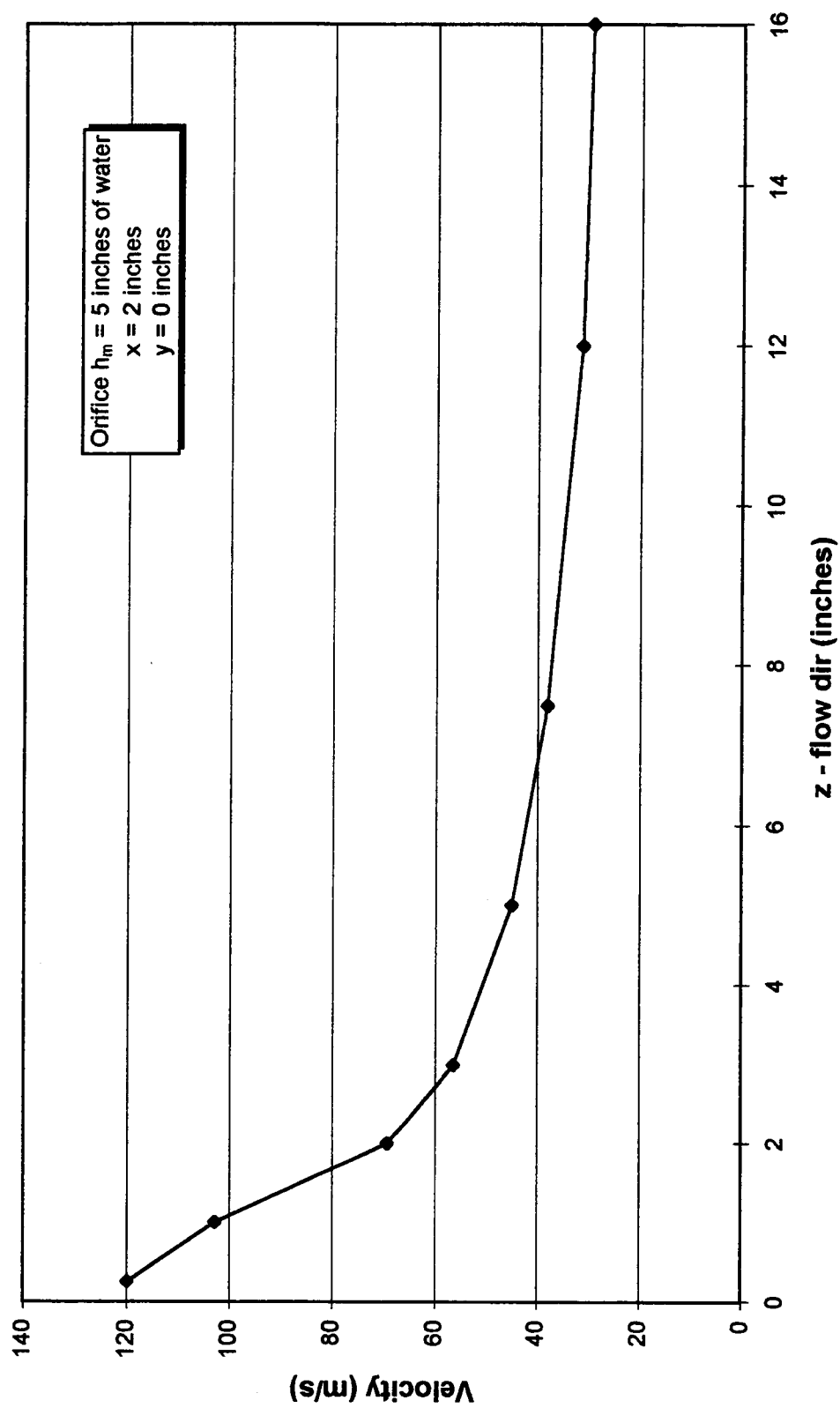


Figure 6.21: Centerline velocity profile measured in the z - direction at a location of $x = 2$ inches and $y = 0$ inches. Measuring orifice delta pressure of 5 inches of water.

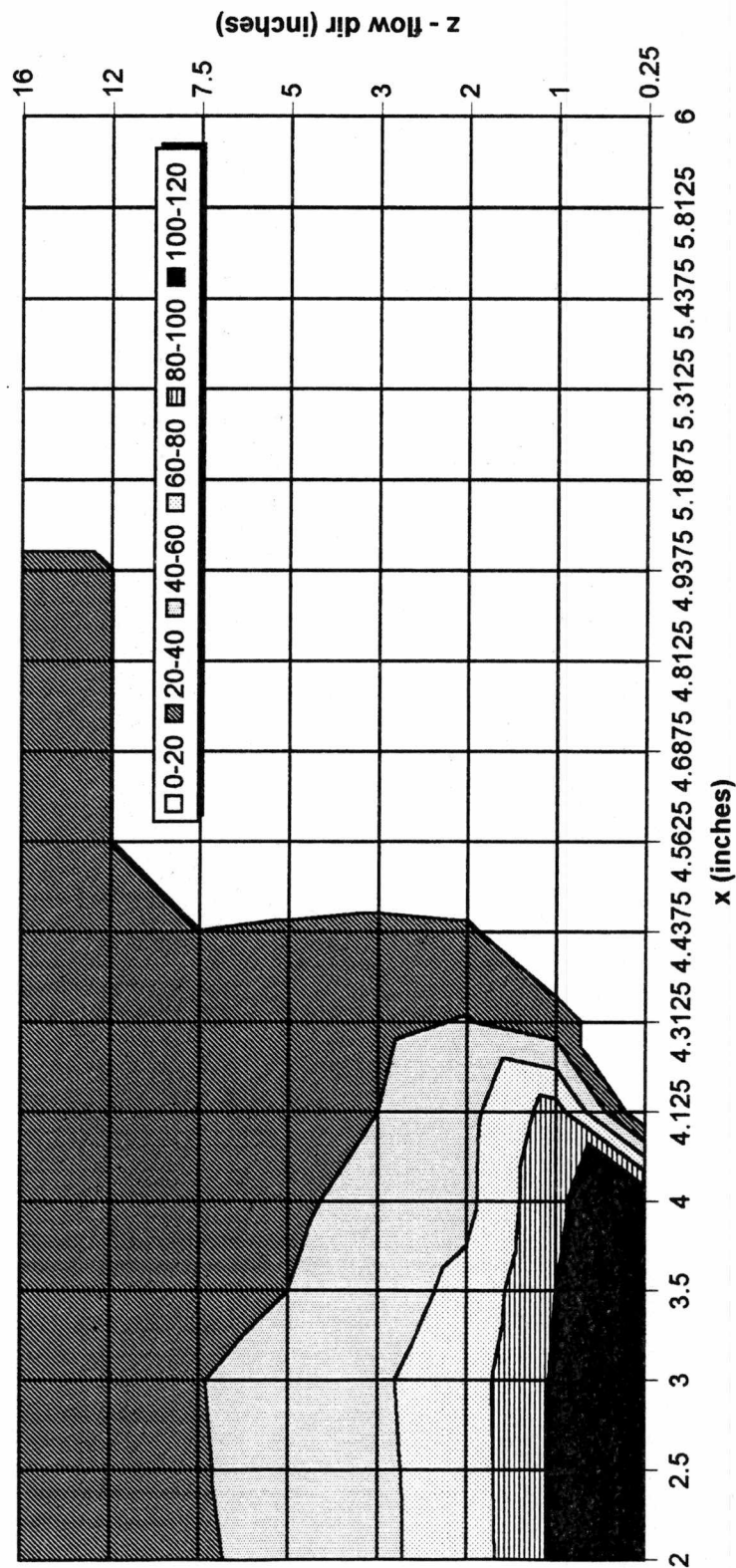


Figure 6.22: Contour plot showing centerline velocities (in m/s) in the x and z plane ($y = 0$ inches). Measuring orifice delta pressure of 5 inches of water.

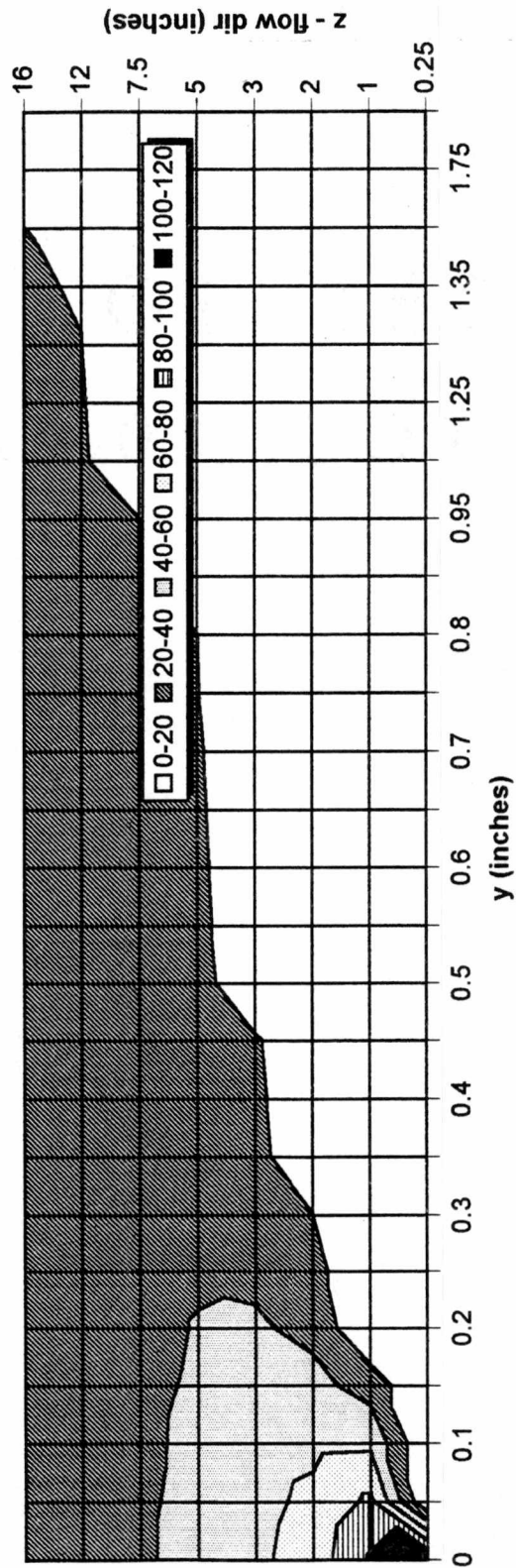


Figure 6.23: Contour plot showing centerline velocities (in m/s) in the y and z plane ($x = 2$ inches). Measuring orifice delta pressure of 5 inches of water.

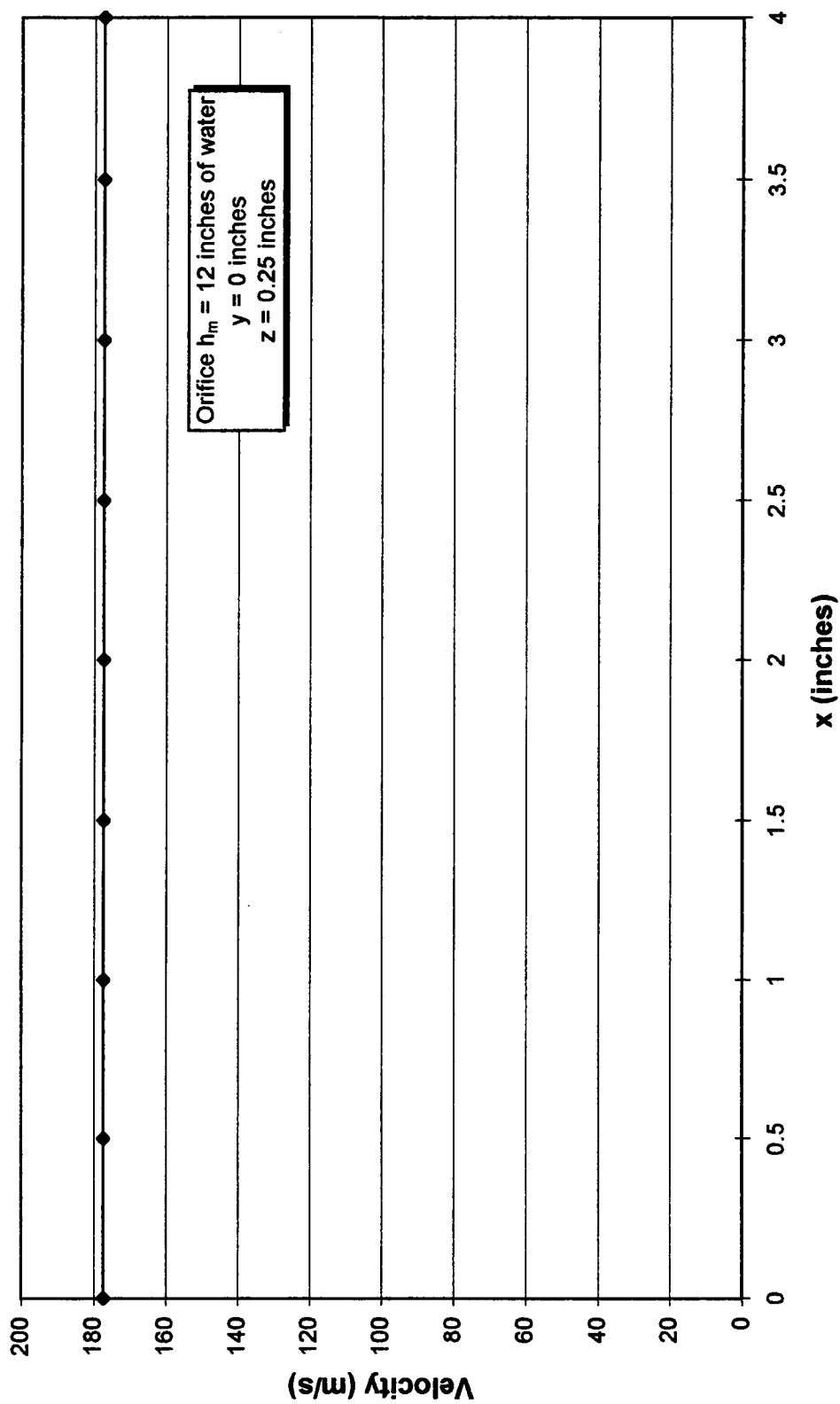


Figure 6.24: Centerline velocity profile measured in the x - direction at a location of $z = 0.25$ inches and $y = 0$ inches. Measuring orifice delta pressure of 12 inches of water.

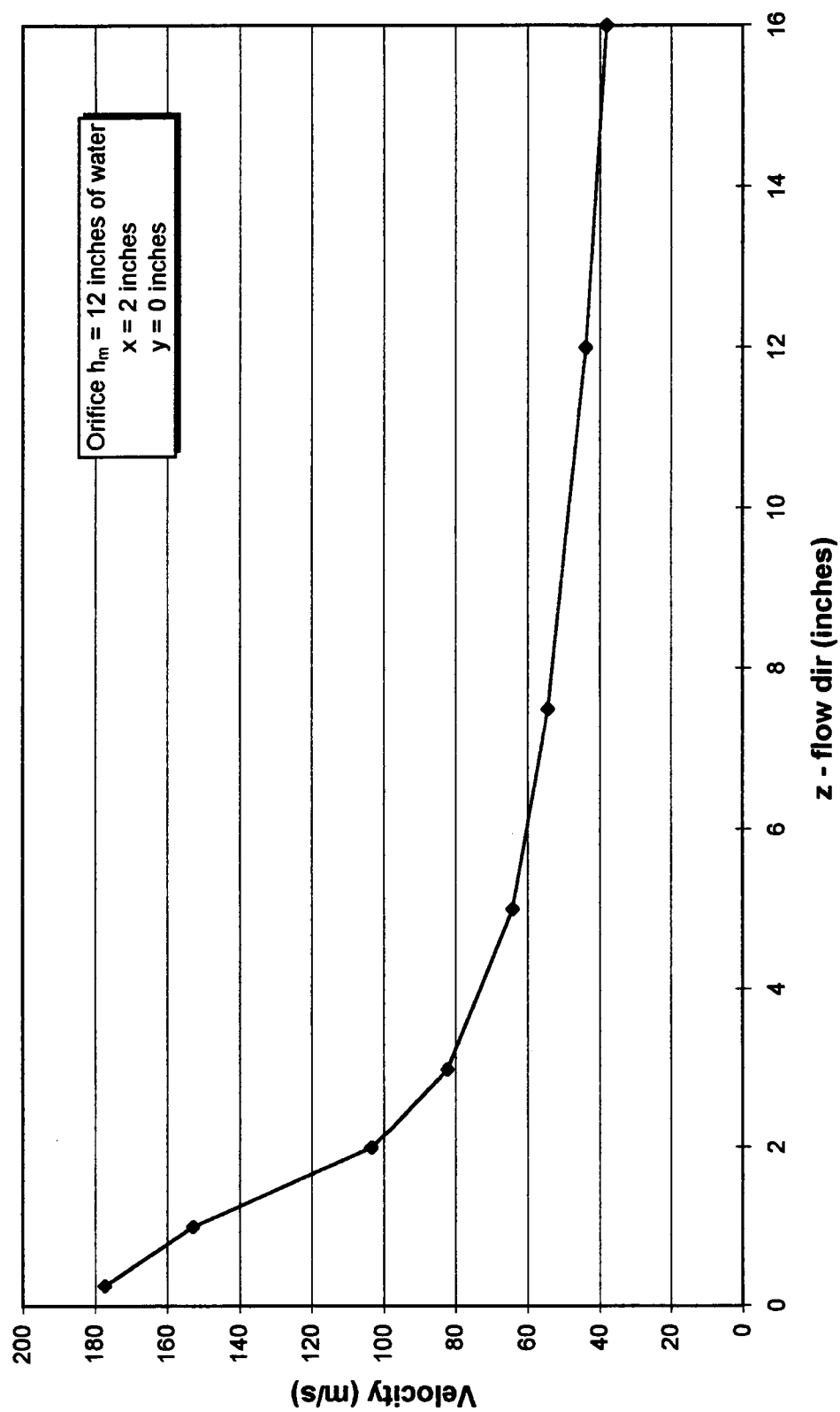


Figure 6.25: Centerline velocity profile measured in the z - direction at a location of $x = 2$ inches and $y = 0$ inches. Measuring orifice delta pressure of 12 inches of water.

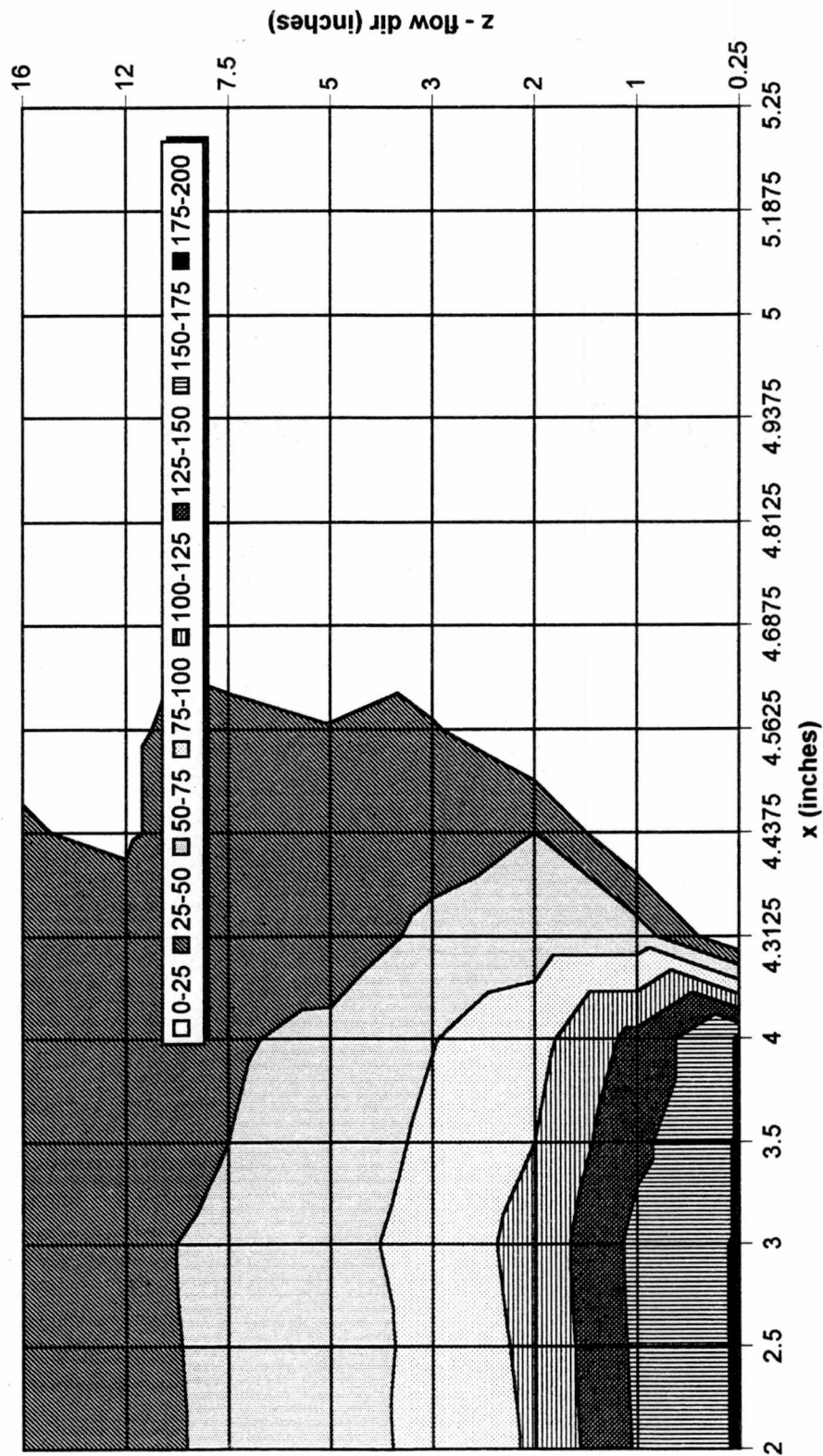


Figure 6.26: Contour plot showing centerline velocities (in m/s) in the x and z plane ($y = 0$ inches). Measuring orifice delta pressure of 12 inches of water.

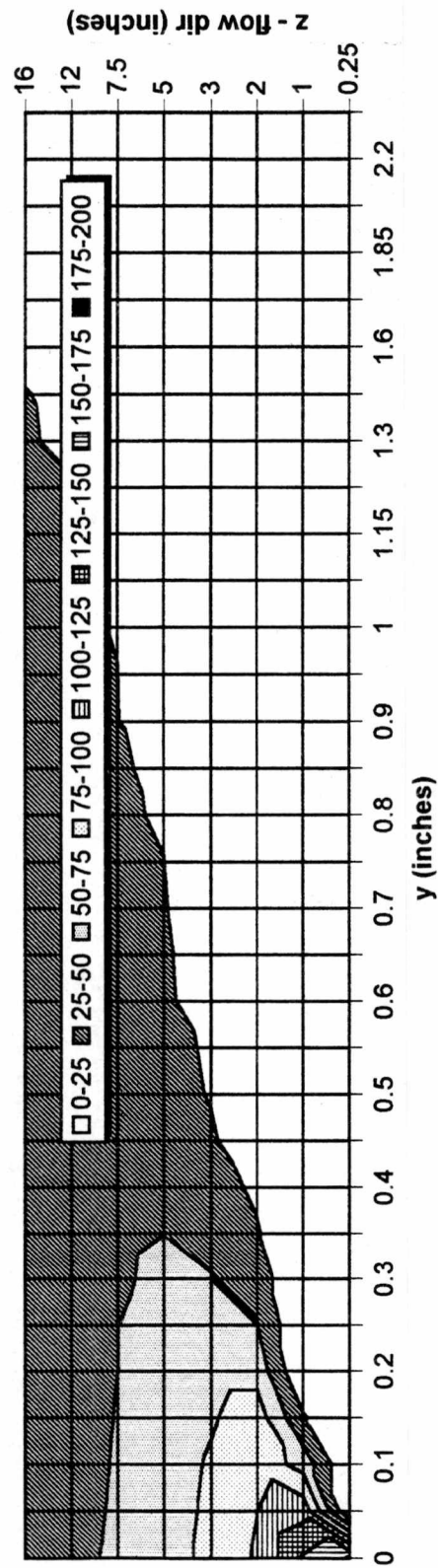


Figure 6.27: Contour plot showing centerline velocities (in m/s) in the y and z plane ($x = 2$ inches). Measuring orifice delta pressure of 12 inches of water.

The findings of this study show that the centerline velocities of the typical melt blown configuration do vary with distance from the die exit; thus, the extruded fibers are exposed to a wide variety of centerline velocity magnitudes.

Investigation of Alternate Nozzle Configurations Resulting in Supersonic Flow

The following sections present results obtained using various configurations of converging - diverging nozzles to determine the effect of supersonic flow on the average fiber diameter. Since the die stagnation pressure was easily measured, and the nozzle exit velocity is a function of die stagnation pressure (keeping stagnation temperatures constant), the following results are presented as functions of die stagnation pressure.

Extension Plates

As was described in Chapter V (Figure 5.1), two flat steel plates were attached to the adjustable face plates of the multi-hole die in order to create a crude converging - diverging nozzle. This study was performed to observe what effect this configuration would have on average fiber diameter and shot intensity values. These results were then compared to results obtained using similar conditions for the converging nozzle configuration. One of the most important findings of this investigation was the observation of some of the fibers colliding with the wall of the "divergent" section created by the extension plates. These collisions were observed to be random, occurring for only a few of

the extruded fibers. Once these fibers collided with either the upper or lower wall, they would then flow along the walls to collect as molten "drops" at the exit plane. These drops were then broken loose by the entrained flow; thus, creating very large shot particles in the collected web samples. Therefore, to avoid these fiber-wall collisions, the extension plates were adjusted to a position (an exit width approximately 0.5 inches) where no fiber-wall interactions could be seen. The results obtained for this configuration are shown in Figures 6.28 through 6.36. Figures 6.28, 6.29, 6.30, and 6.31 depict graphs of average fiber diameter versus die stagnation pressure (keeping polymer temperature constant) for the configurations with and without the extension plates. In each of these figures, the average fiber diameter resulting from the use of extension plates was found to be consistently smaller than those obtained using the converging nozzle configuration. The results found for the shot intensity comparison are shown in Figures 6.32 through 6.35. Upon examination of these results, it was found that only one case ($T_{air} = 450$ degrees Fahrenheit) exhibited smaller shot intensity values for the extension plate configuration. This case is shown in Figure 6.35. The shot intensity values of the other air temperatures were found to be highly sporadic. Since no apparent trend could be found for the shot intensity results, no conclusions were made concerning the effect extension plates had on shot intensity values. Figure 6.36 shows shot intensity values decreasing with decreasing air temperature. This finding supports the conclusions stated earlier in this chapter for the investigations on polymer temperature and fiber motion. In short, by decreasing the air temperature, the extruded fibers will reach their solidification temperatures much sooner.

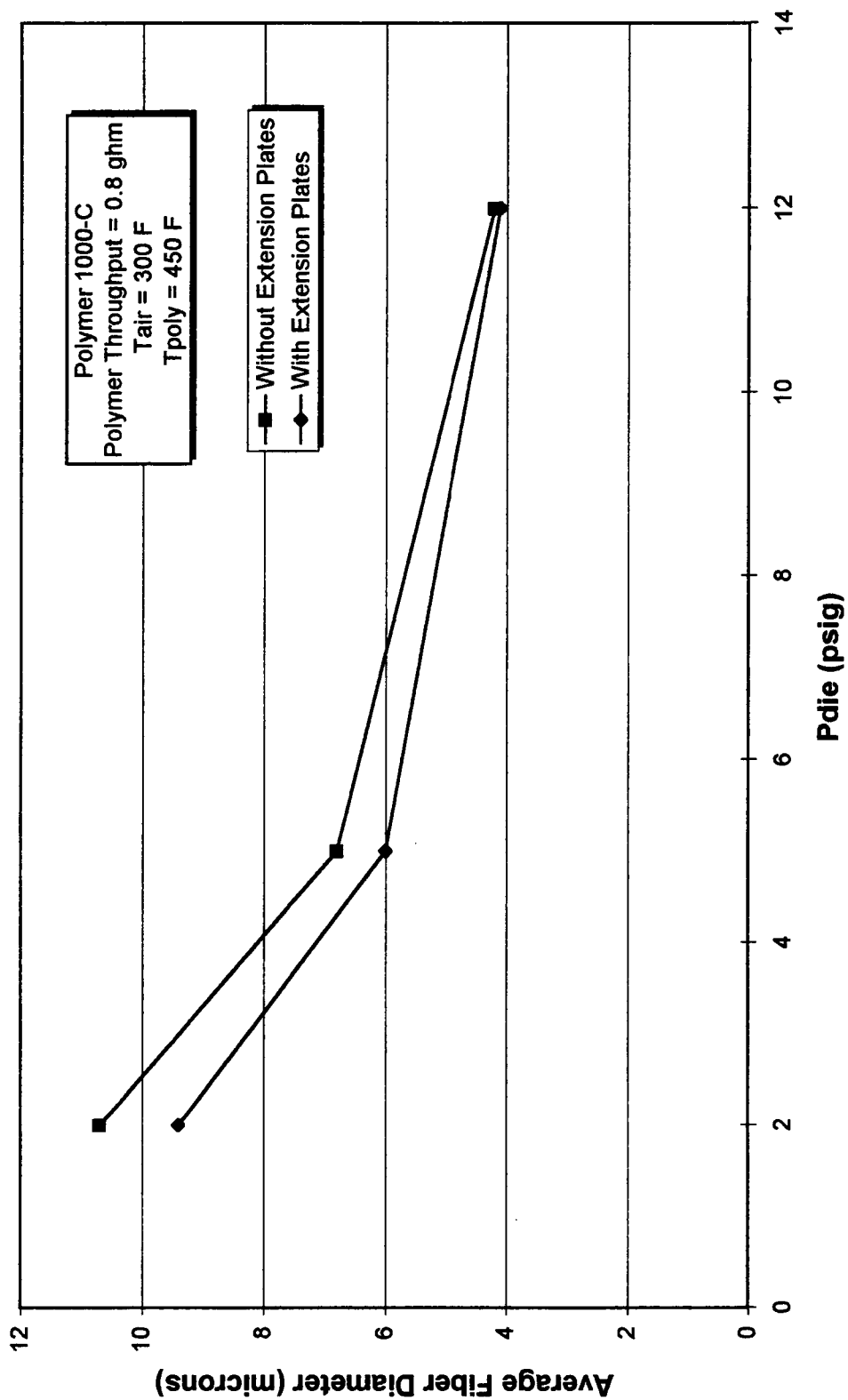


Figure 6.28: Comparison of average fiber diameters using extension plates, for air temperature of 300 degrees Fahrenheit and polymer temperature of 450 degrees Fahrenheit.

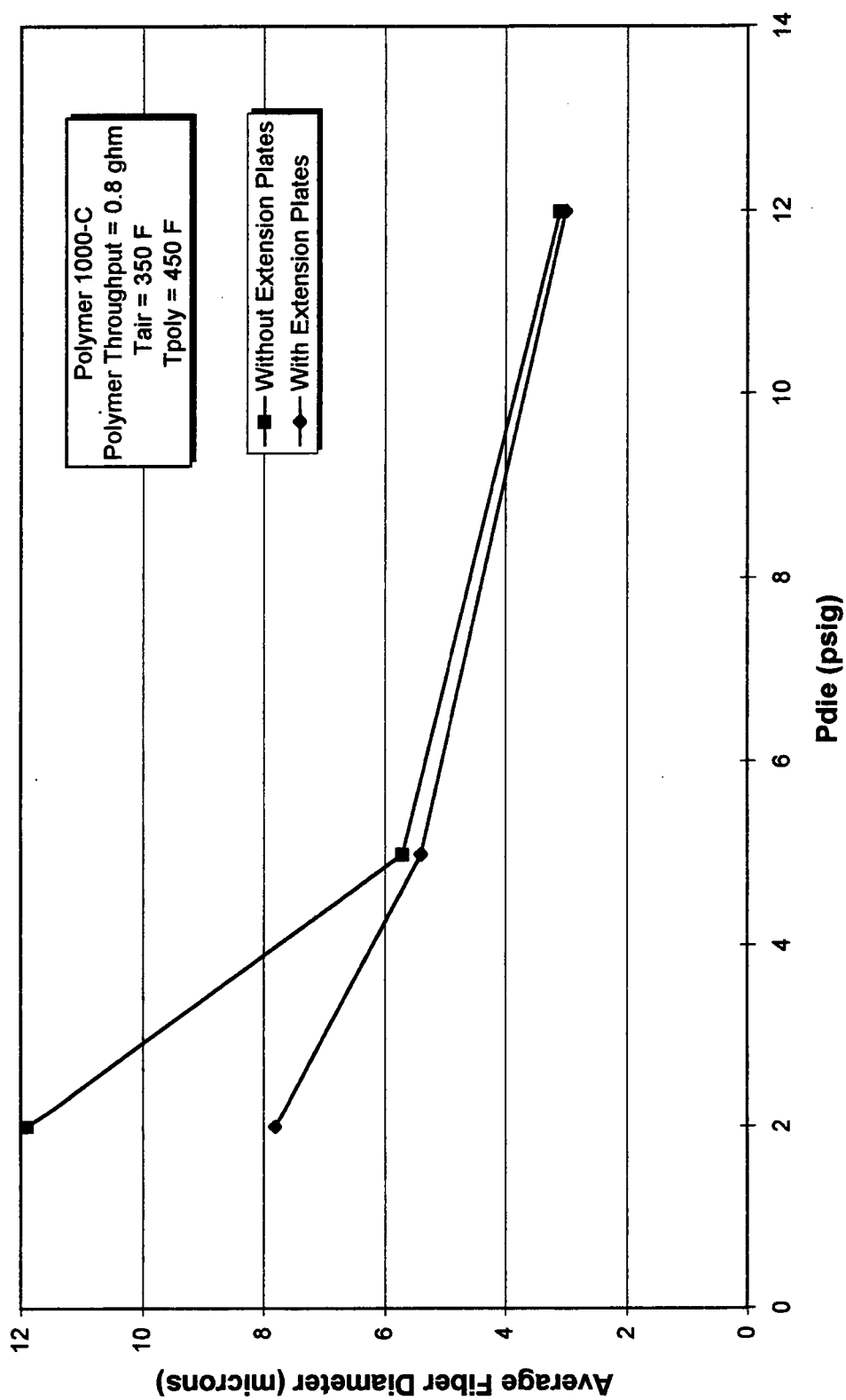


Figure 6.29: Comparison of average fiber diameters using extension plates, for air temperature of 350 degrees Fahrenheit and polymer temperature of 450 degrees Fahrenheit.

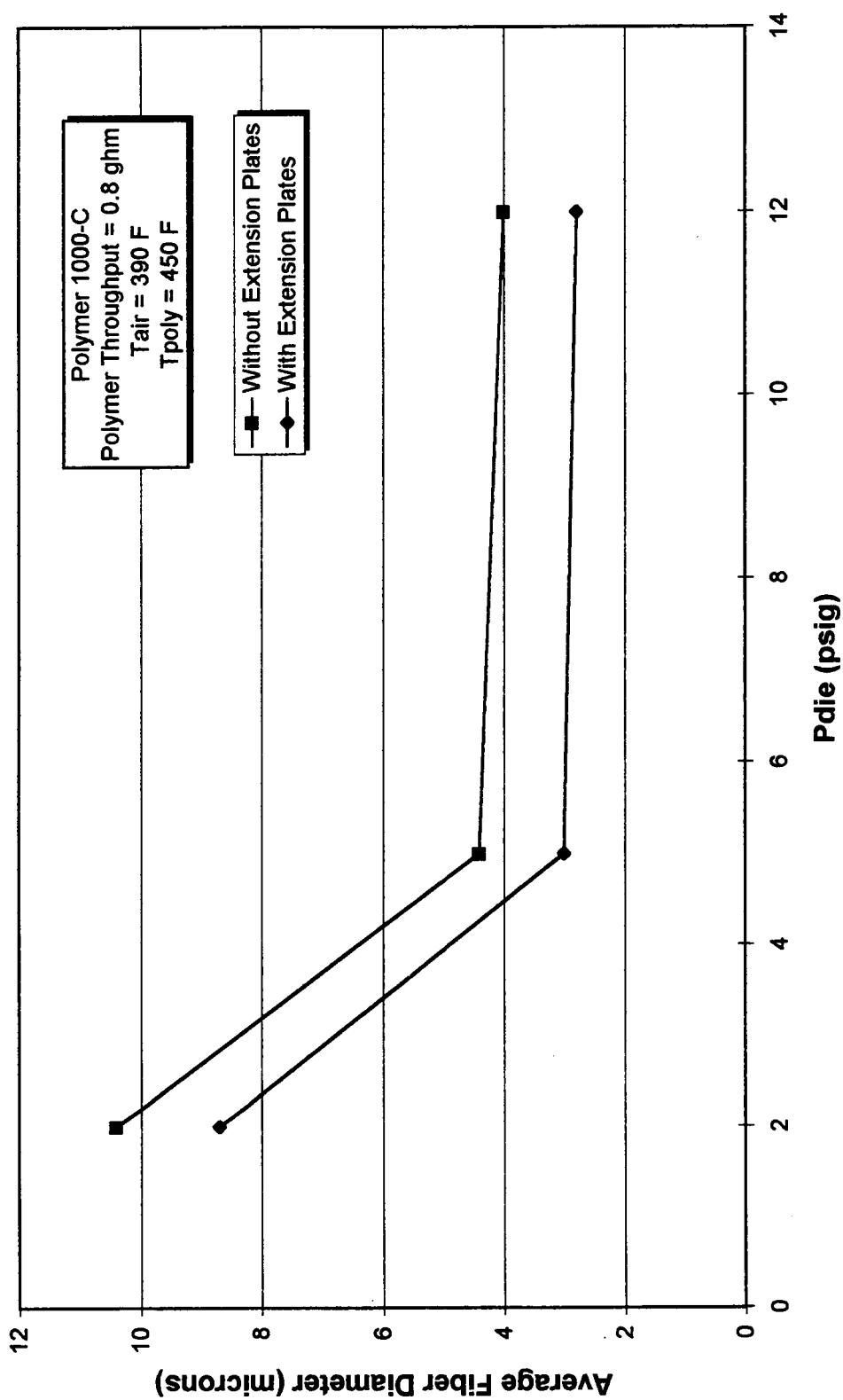


Figure 6.30: Comparison of average fiber diameters using extension plates, for air temperature of 390 degrees Fahrenheit and polymer temperature of 450 degrees Fahrenheit.

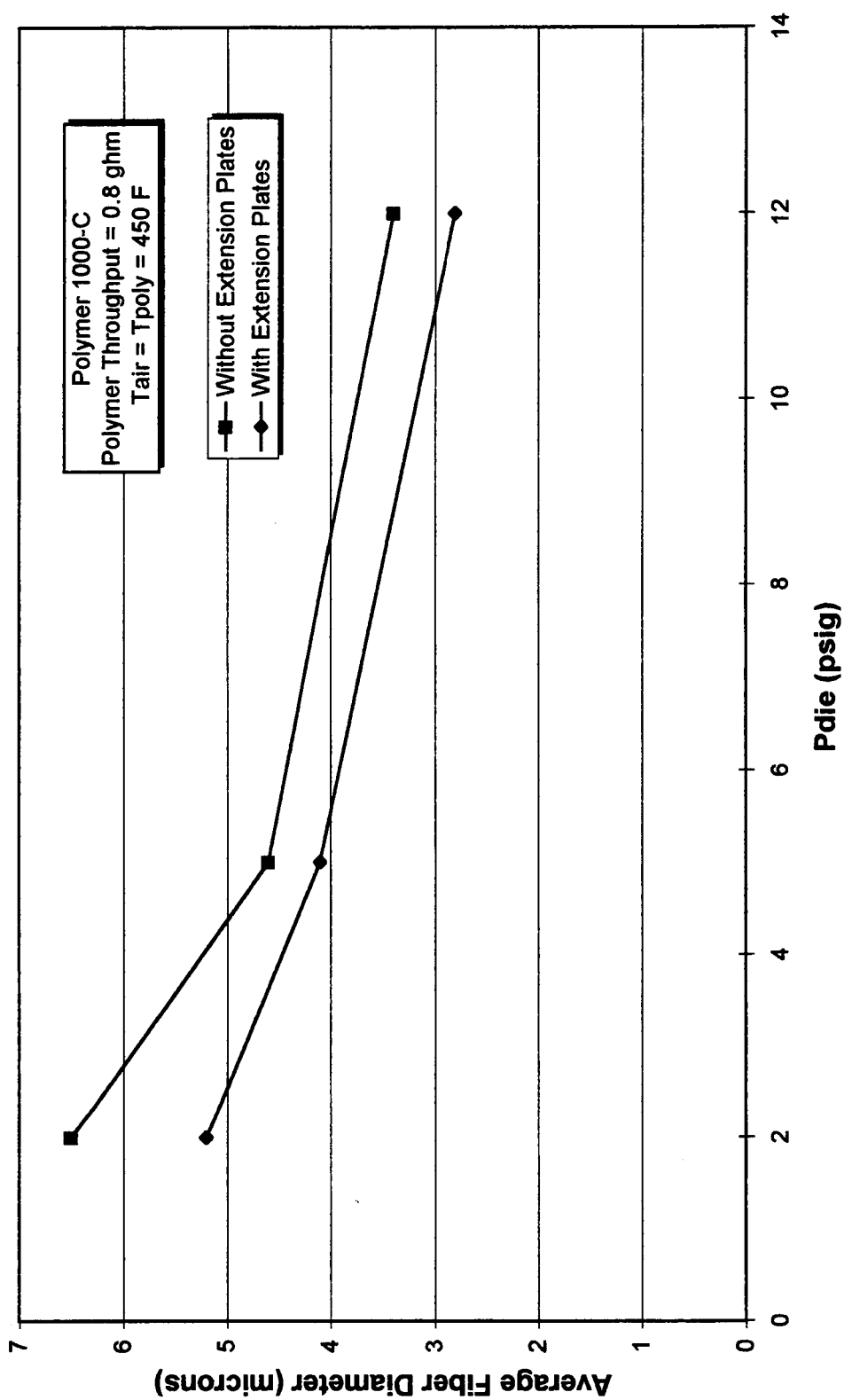


Figure 6.31: Comparison of average fiber diameters using extension plates, for air temperature of 450 degrees Fahrenheit and polymer temperature of 450 degrees Fahrenheit.

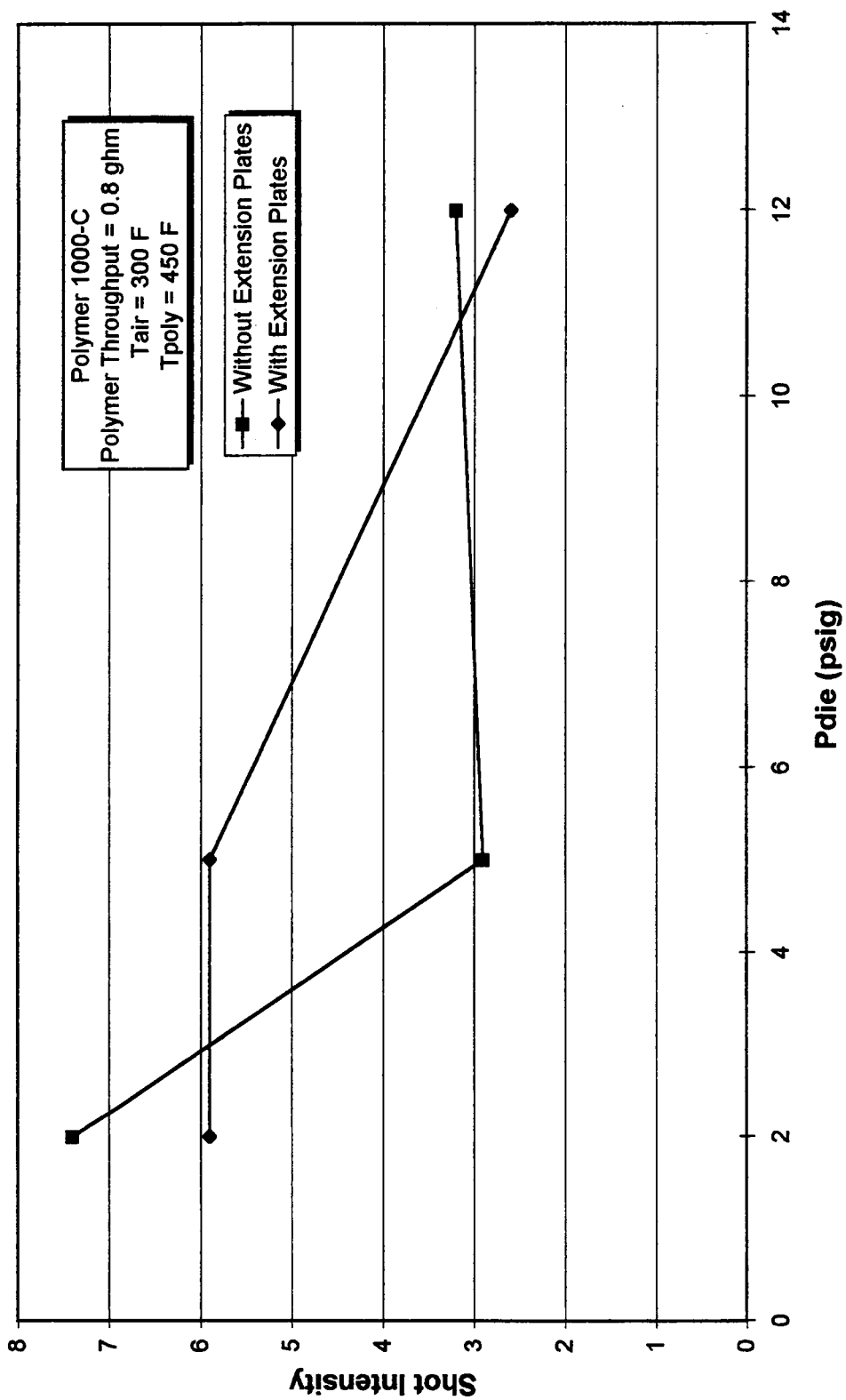


Figure 6.32: Comparison of shot intensity using extension plates, for air temperature of 300 degrees Fahrenheit and polymer temperature of 450 degrees Fahrenheit.

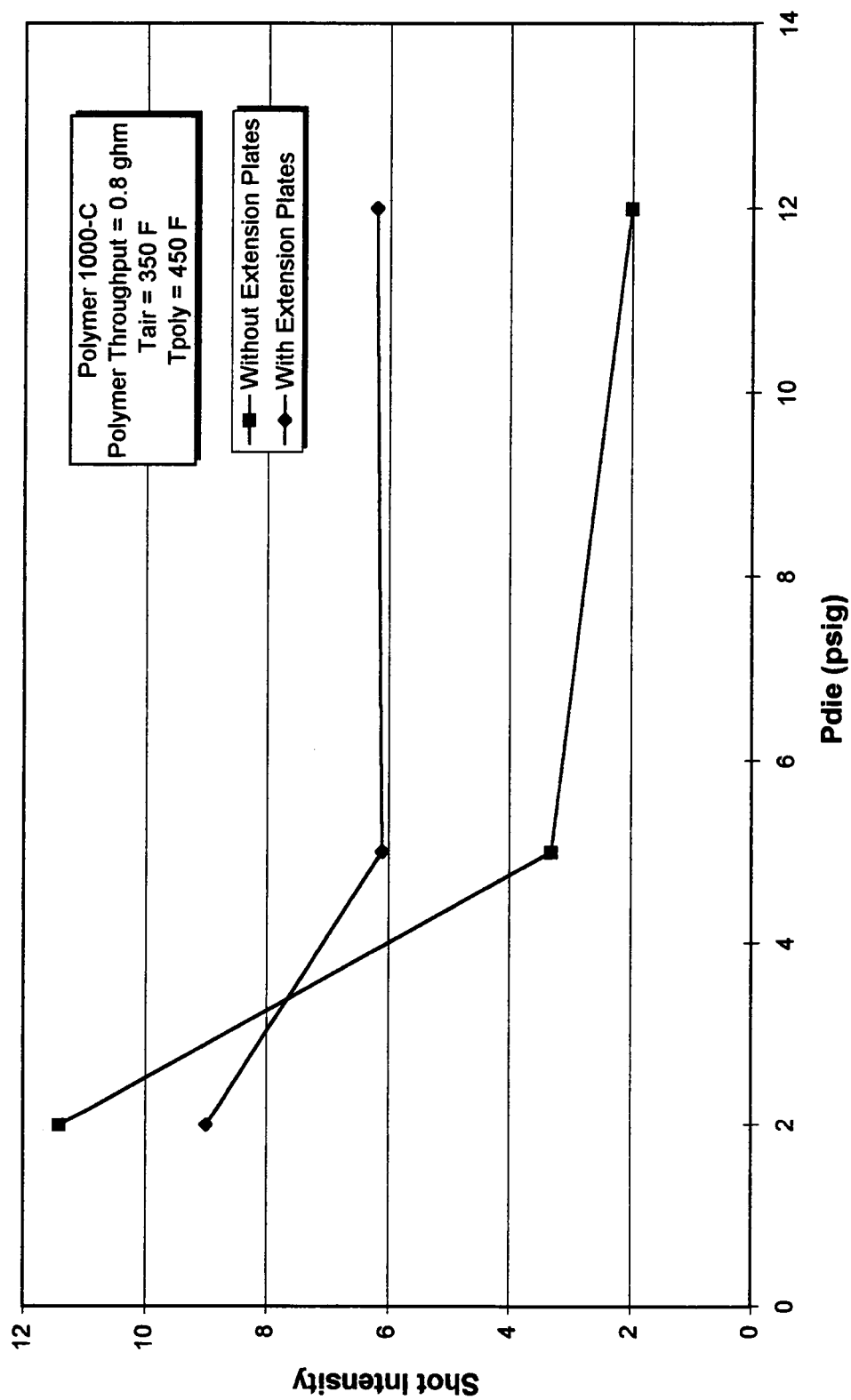


Figure 6.33: Comparison of shot intensity using extension plates, for air temperature of 350 degrees Fahrenheit and polymer temperature of 450 degrees Fahrenheit.

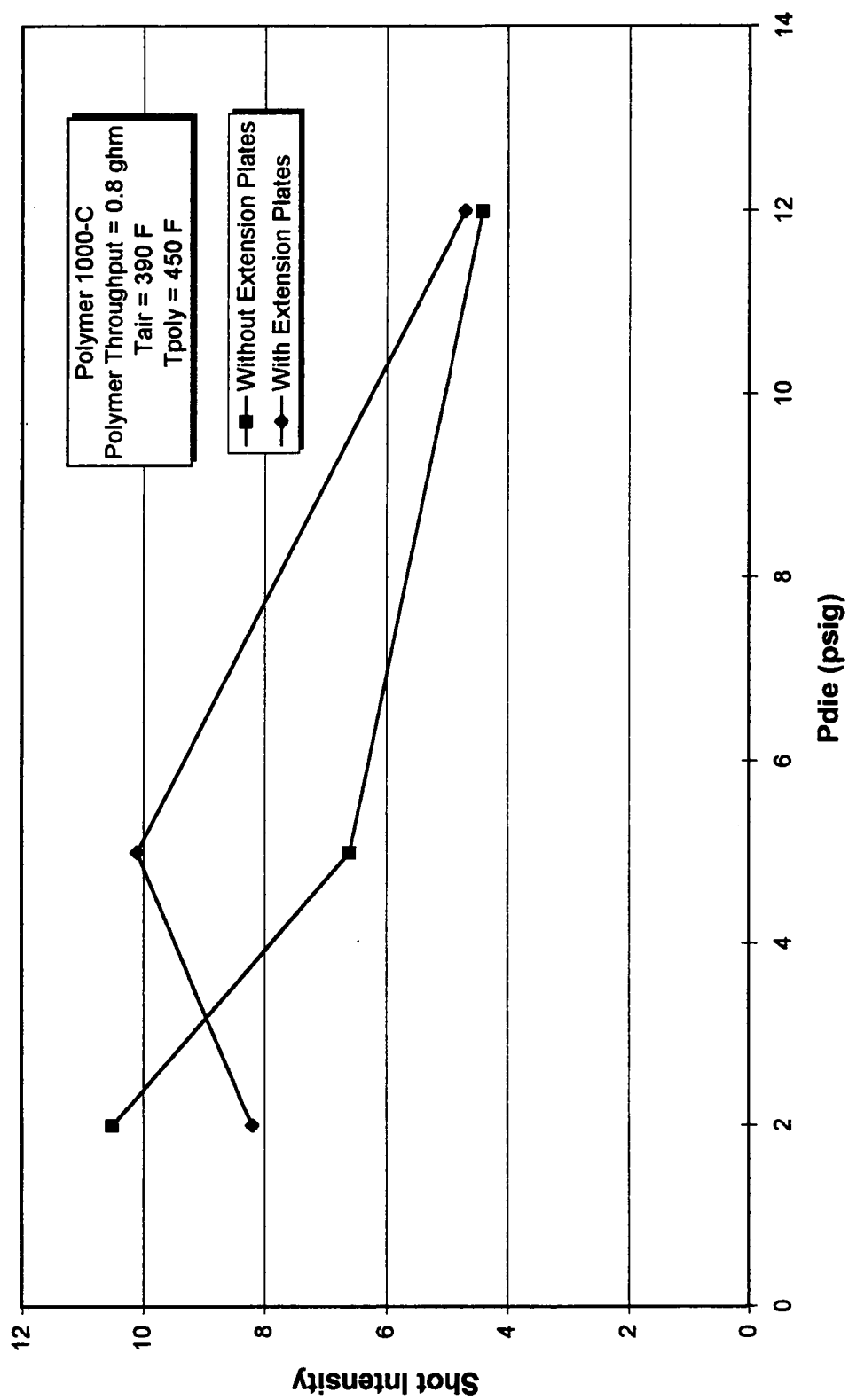


Figure 6.34: Comparison of shot intensity using extension plates, for air temperature of 390 degrees Fahrenheit and polymer temperature of 450 degrees Fahrenheit.

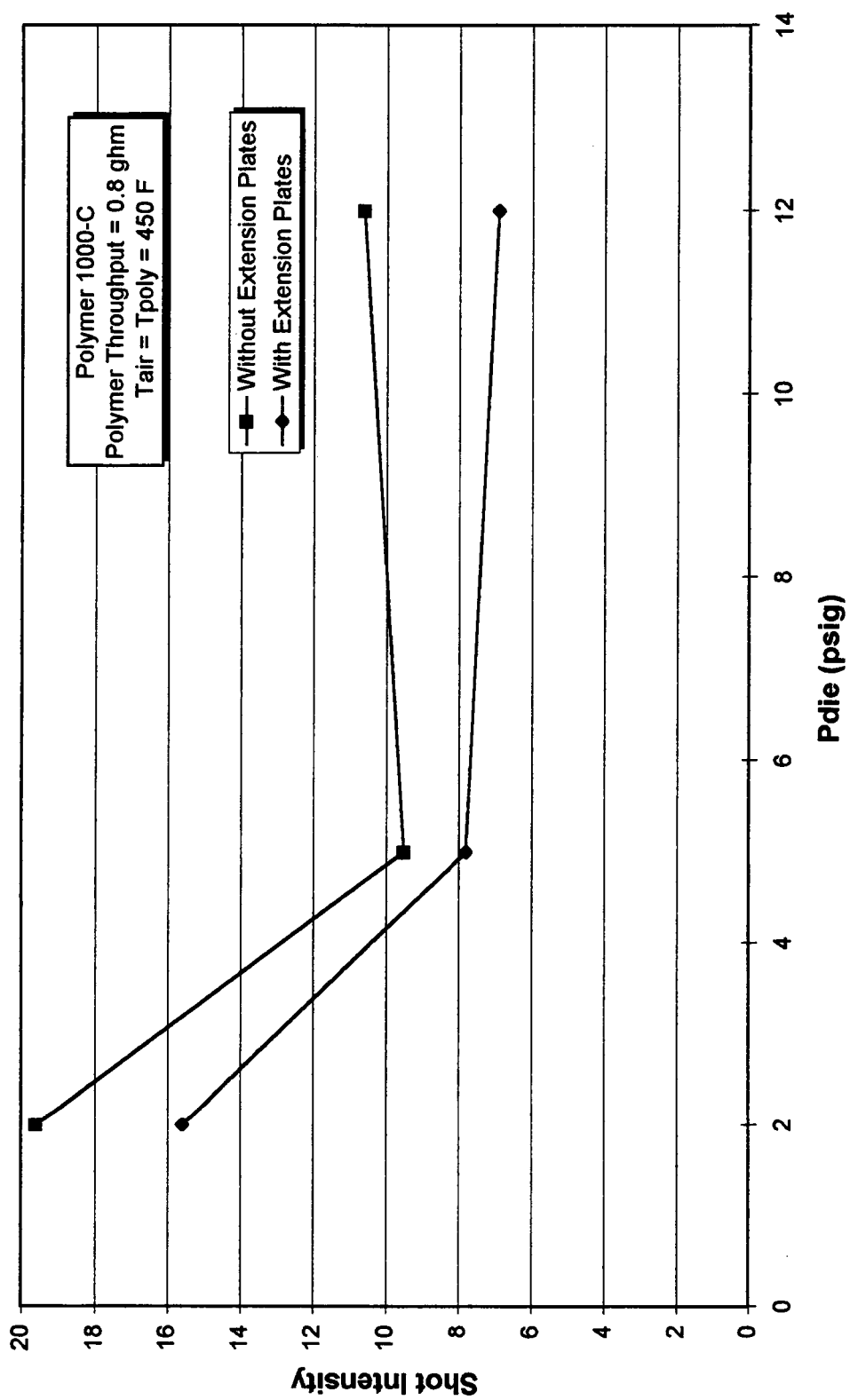


Figure 6.35: Comparison of shot intensity using extension plates, for air temperature of 450 degrees Fahrenheit and polymer temperature of 450 degrees Fahrenheit.

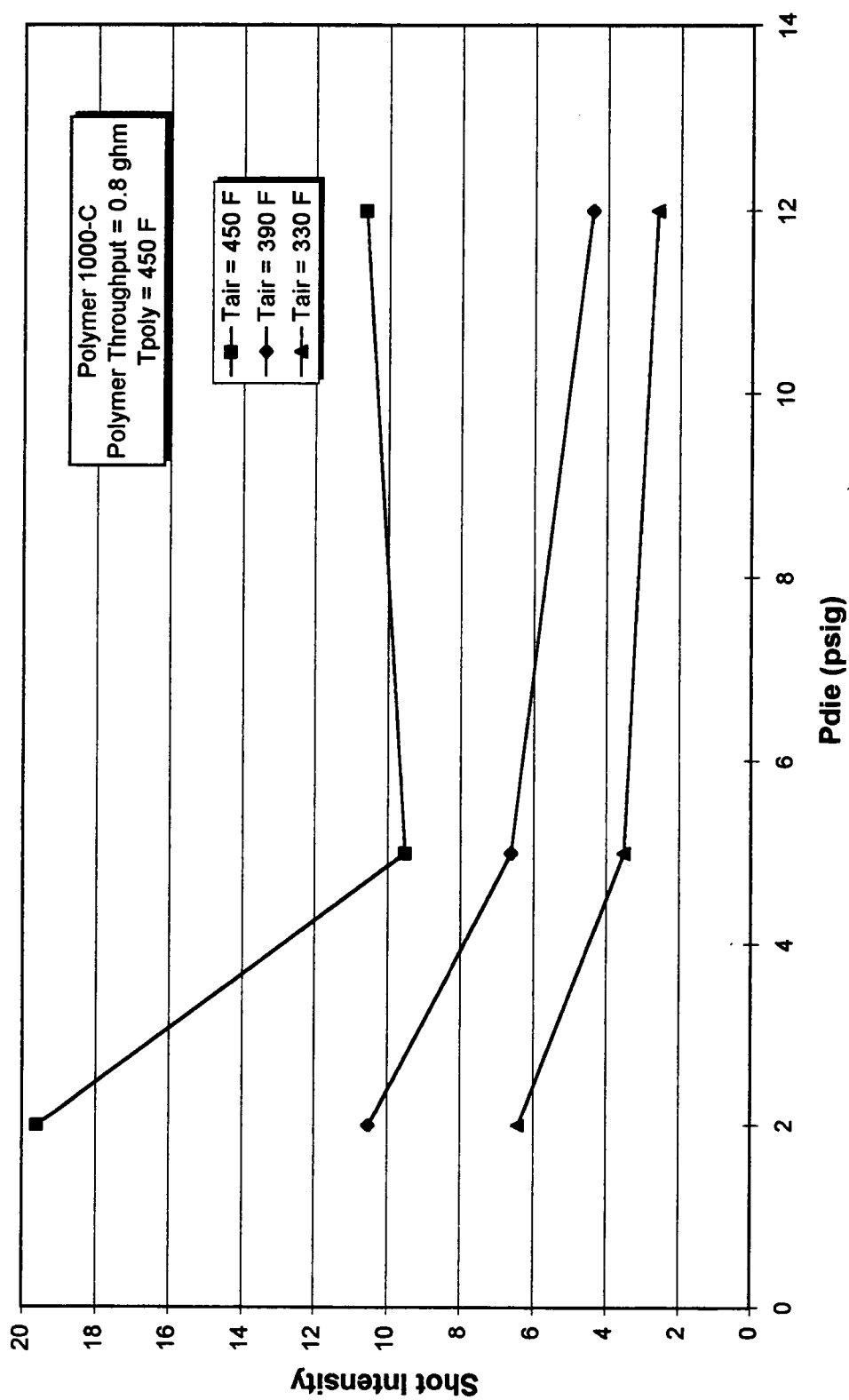


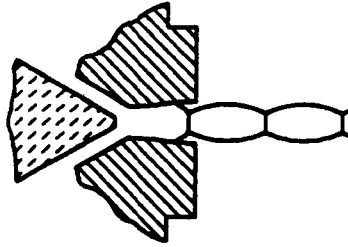
Figure 6.36: Effect of air temperature on shot intensity, for air temperatures between 450 and 330 degrees Fahrenheit.

The advantage of these quicker solidification times, as was mentioned earlier, is a decrease in the chance of fiber-to-fiber fusing. Findings similar to these for shot rating values were experienced by Milligan [22] during his use of cool cross-flow air to improve nonwoven melt blown fibers [9].

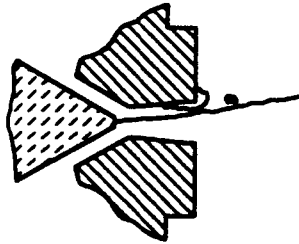
The findings of this investigation suggest that smaller average fiber diameters can be obtained by increasing the air exit velocity and shot can be decreased by cooling the extruded fibers below their solidification temperatures, thus, decreasing fiber-to-fiber fusions.

Downstream Converging - Diverging Nozzle

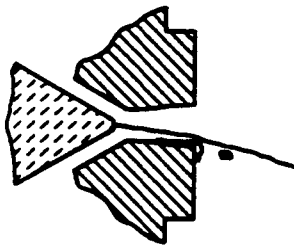
Before presenting the findings pertaining to average fiber diameters, various remarks about the behavior of the fiber flow field within and upon exiting the divergent section of the converging - diverging nozzle will be made. For this investigation, two configurations of die setback (ds) and air gap (dg) were examined. These were (1) $ds = dg = 0.079$ inches (2 millimeters) and (2) $ds = 0.158$ inches (4 millimeters), $dg = 0.125$ inches (3.175 millimeters). As stated in Chapter V, initially a shadowgraph was performed on each configuration, without polymer flow, to determine whether or not supersonic flow conditions had been achieved at the nozzle exit plane. The results of this technique showed strong compression and expansion waves (shock diamonds or crows feet) at the exit of the nozzle for die stagnation pressures higher than 30 pounds per square inch gage. These diamonds are shown in the first drawing of Figure 6.37. The presence of such diamonds is



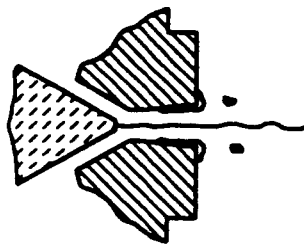
NO POLYMER FLOW,
SHOWING SHOCK "DIAMONDS"



WITH POLYMER FLOW,
SHOWING SEPARATED FLOW
ON LOWER NOZZLE WALL



WITH POLYMER FLOW,
SHOWING SEPARATED FLOW
ON UPPER NOZZLE WALL



WITH POLYMER FLOW,
SHOWING NO SEPARATED FLOW
AT SUPERSONIC CONDITIONS

Figure 6.37: Observations of fiber interactions with the divergent section walls.

an indication that the nozzle exit air flowfield is supersonic. Knowing that supersonic velocities were obtainable at the nozzle exit plane, polymer fibers were then extruded to observe the fiber-to-wall behavior within the divergent section. Examining the first configuration of ds and dg, the behavior of the extruded fibers closely resembled that of the previous extension plate investigation. At subsonic conditions, some of the molten polymer fibers would collide with the upper and lower walls of the divergent section immediately upon passing through the nozzle throat. The point of collision (upper or lower wall) was highly dependent upon whether or not a separated flow region had been established within the divergent section. This separation region would cause the extruded fibers to alternately collide with either the upper or lower wall of the divergent section. A representation of this phenomena is shown in the second and third drawings of Figure 6.37. As in the extension plate study, once the polymer had collided with the nozzle wall, it would then flow towards the exit plane, where it collected into a large molten pool forming drops (globs) of polymer on the die face plate. These drops would then be pulled off by the entrained flow, consequently, littering the web sample with both types of the shot particles described earlier in this chapter. The separated regions observed during subsonic flow would disappear once supersonic conditions were achieved within the divergent section. At these conditions, rather than polymer collecting on either the upper or lower wall, an equal amount was observed to collide immediately downstream of the nozzle throat, where it would then collect and flow along both walls. This is shown in the last drawing of Figure 6.37. The findings for the second ds - dg configuration were

identical to the first, with the exception of the amount of polymer that "dripped" from the die face plate. As the die setback and air gap was increased, less polymer would collide and flow down the nozzle walls, thus, resulting in a smaller amount of molten polymer dripping from the die face plate.

From the observations mentioned above, it is apparent that the extruded fibers exhibited difficulties upon traversing the sonic throat and divergent section of the nozzle. In addition to colliding with the divergent section wall, some fibers collided with each other. These collisions resulted in the web samples containing large amounts of shot. Since the production of small fibers was the main goal of this investigation, no shot intensity measurements were made.

The results of the fiber diameter measurements, for the two configurations of d_s and d_g described earlier, are shown in Figures 6.38 and 6.39. For $d_s = d_g = 0.079$ inches, polymer temperature of 450 degrees Fahrenheit, and an air temperature of 460 degrees Fahrenheit, Figure 6.38 shows the average fiber diameter first decreasing in value, then slightly increasing in value as the die stagnation pressure was increased. Figure 6.39 shows similar results for the case of increased die setback and air gap. Although the average fiber diameters for both cases were found to be larger than the desired 1 micron, a similar trend can be seen in both figures. Looking at Figures 6.38 and 6.39, the average fiber diameter appears to approach an asymptotic value between 3 and 4.5 microns. These findings are similar to those found by Spencer [14] during his investigation of fiber diameter dependence on polymer temperature using the typical melt blowing configuration and a single hole die. Spencer found that, at various air jet temperatures, as the air exit

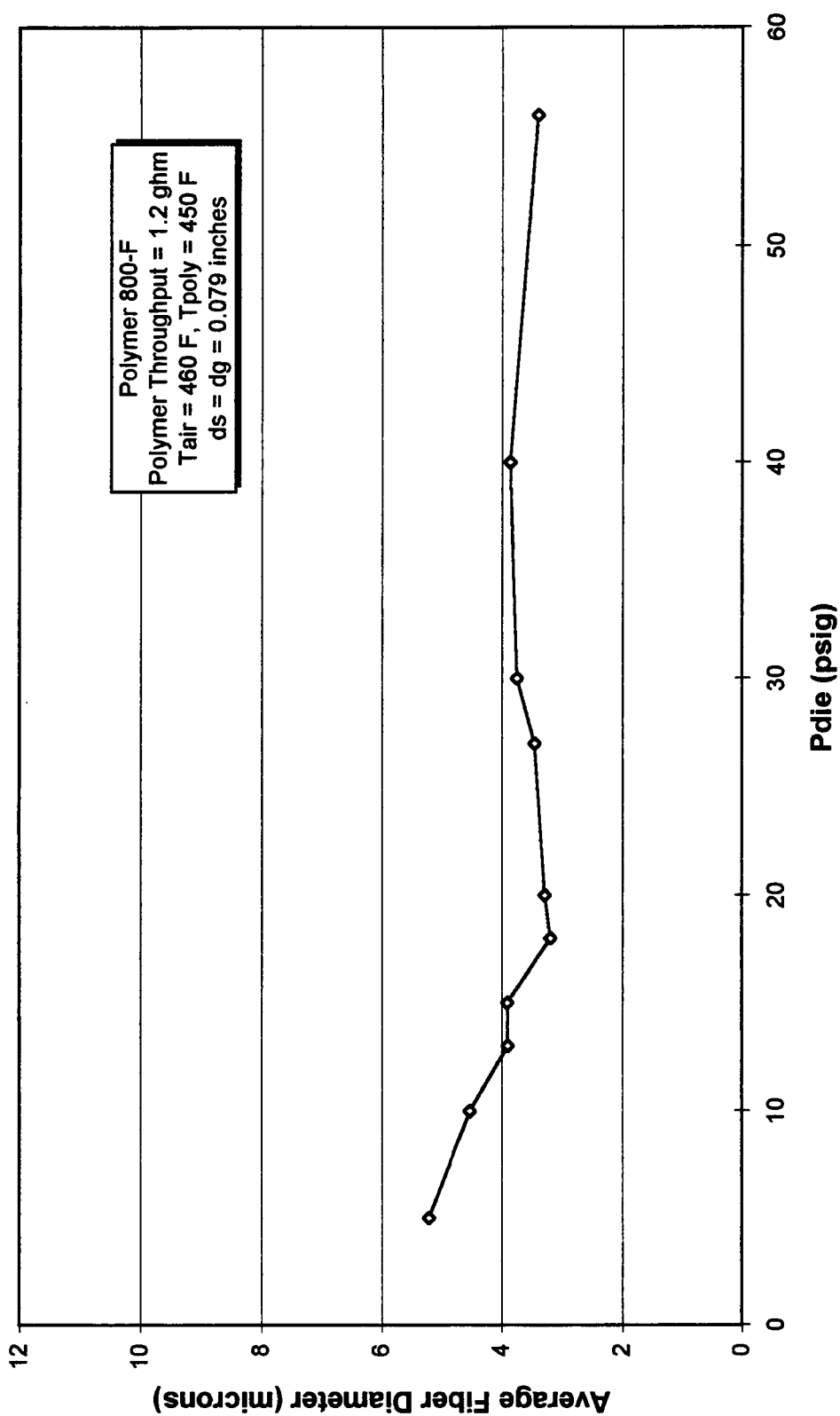


Figure 6.38: Average fiber diameter results obtained using the downstream converging - diverging nozzle configuration (ds = dg = 0.079 inches).

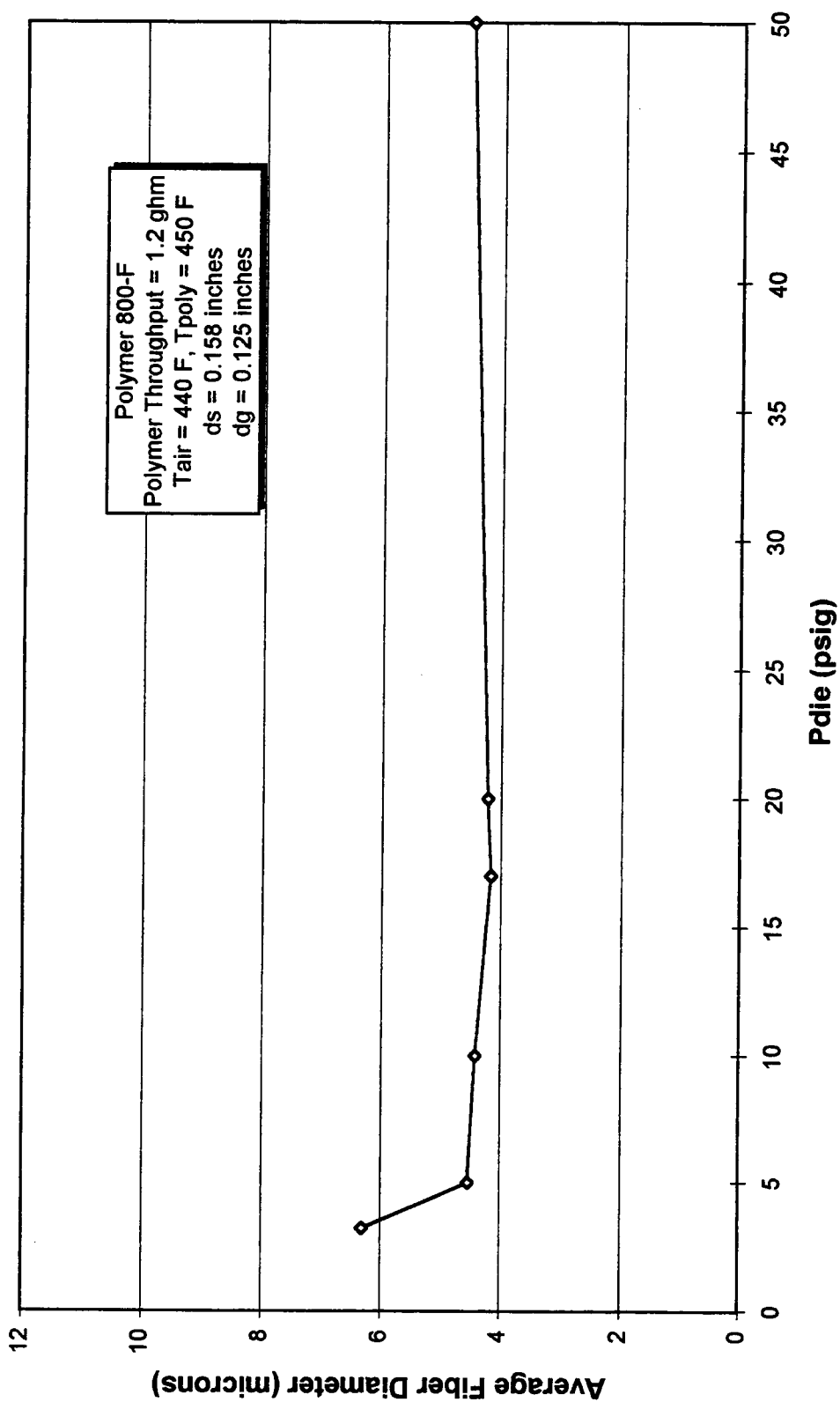


Figure 6.39: Average fiber diameter results obtained using the downstream converging - diverging nozzle configuration (ds = 0.158 inches, dg = 0.125 inches).

velocity was increased, average fiber diameters would consistently converged to values between 4 and 6 microns. This suggests that extruded fibers can be drawn up to some asymptotic value corresponding to a given polymer temperature. Since rheological forces within a fiber are highly dependent upon the solidification temperature of the fiber, the asymptotic value would change as polymer temperature changed. This asymptotic value would ideally be where the rheological force within the fiber equals the drawing force (drag) on the fiber, neglecting gravity.

The findings of this investigation were: (1) with increasing air velocity, the reduction in fiber diameters appears to approach some asymptotic value between 3 and 4.5 microns, and (2) as the extruded molten fibers pass through shock waves and/or separation regions located within the divergent section, fiber collisions can occur with both the nozzle wall and each other resulting in the production of large amounts of shot.

Modified Downstream Converging - Diverging Nozzle

The following two sections present average fiber diameter results obtained using the multi- and single hole dies in conjunction with the previous downstream converging - diverging nozzle having 1/4 inch of material milled off at the divergent section exit plane.

Multi-Hole Die

Similar to the downstream c-d nozzle before being modified, two die setback (0.079 and 0.158 inches) and air gap (0.079 and 0.125 inches) configurations were

examined in this investigation. Upon observing the behavior of the molten fibers through the throat and divergent section for this nozzle, the fiber-to-wall and fiber-to-fiber interactions were found to be identical to the ones reported for the previous unmodified c-d nozzle; thus, alleviating the need to perform shot intensity measurements. The results obtained concerning the affect this nozzle configuration had on average fiber diameter, for ds and dg values of 0.079 inches, are shown in Figures 6.40 and 6.41. Figure 6.40 shows the average fiber diameter asymptotically approaching an approximate value of 2.75 microns with increasing die stagnation pressure. The test conditions that samples were collected for in this figure was air and polymer temperatures of 550 degrees Fahrenheit. A similar asymptotic trend approaching approximately 4 microns is shown in Figure 6.41 for air and polymer temperatures of 450 degrees Fahrenheit. The results obtained for an increase in die setback and air gap were consistent to those found in Figures 6.40 and 6.41. For ds = 0.158 inches and dg = 0.125 inches, Figures 6.42 and 6.43 show fiber diameters asymptotically approaching a value between 2.5 and 4 microns. The findings of this investigation are very similar to those obtained at the same polymer temperatures, in the previous unmodified c-d nozzle investigation. These results support the idea that the fiber diameters appear to approach an asymptotic value defined by the polymer temperature.

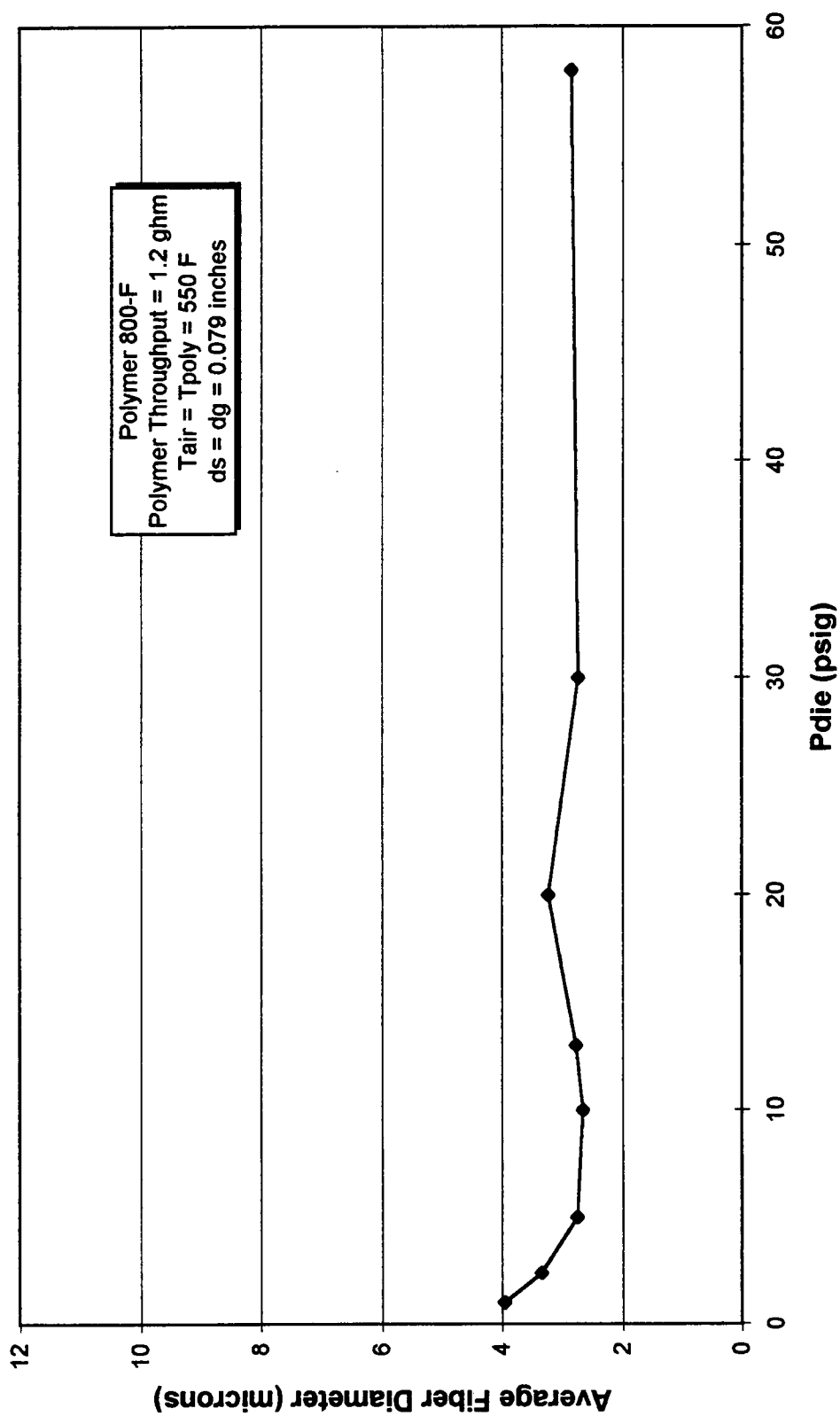


Figure 6.40: Average fiber diameter results obtained using the modified downstream converging - diverging nozzle configuration (ds = dg = 0.079 inches), for air and polymer temperatures of 550 degrees Fahrenheit.

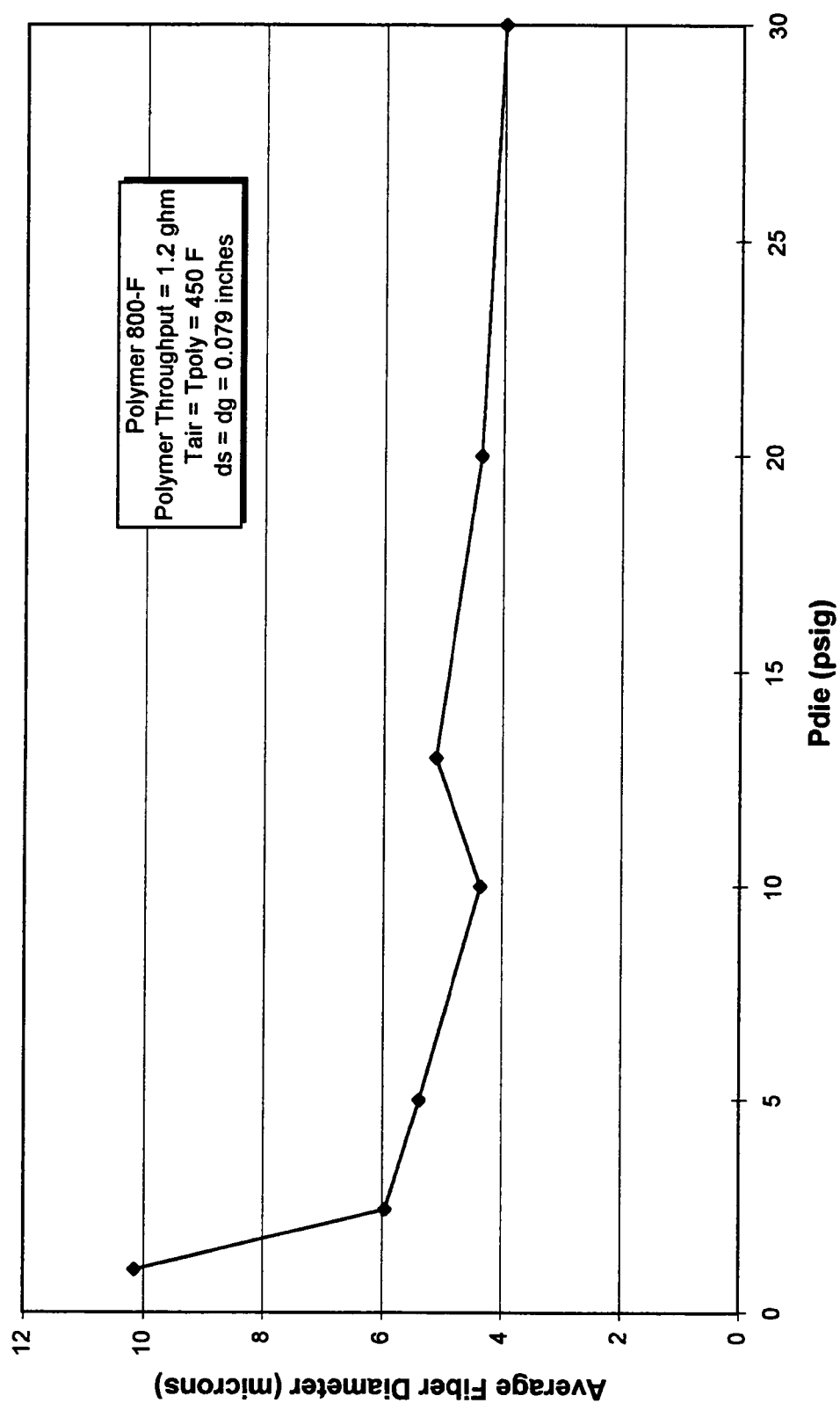


Figure 6.41: Average fiber diameter results obtained using the modified downstream converging - diverging nozzle configuration (ds = dg = 0.079 inches), for air and polymer temperatures of 450 degrees Fahrenheit.

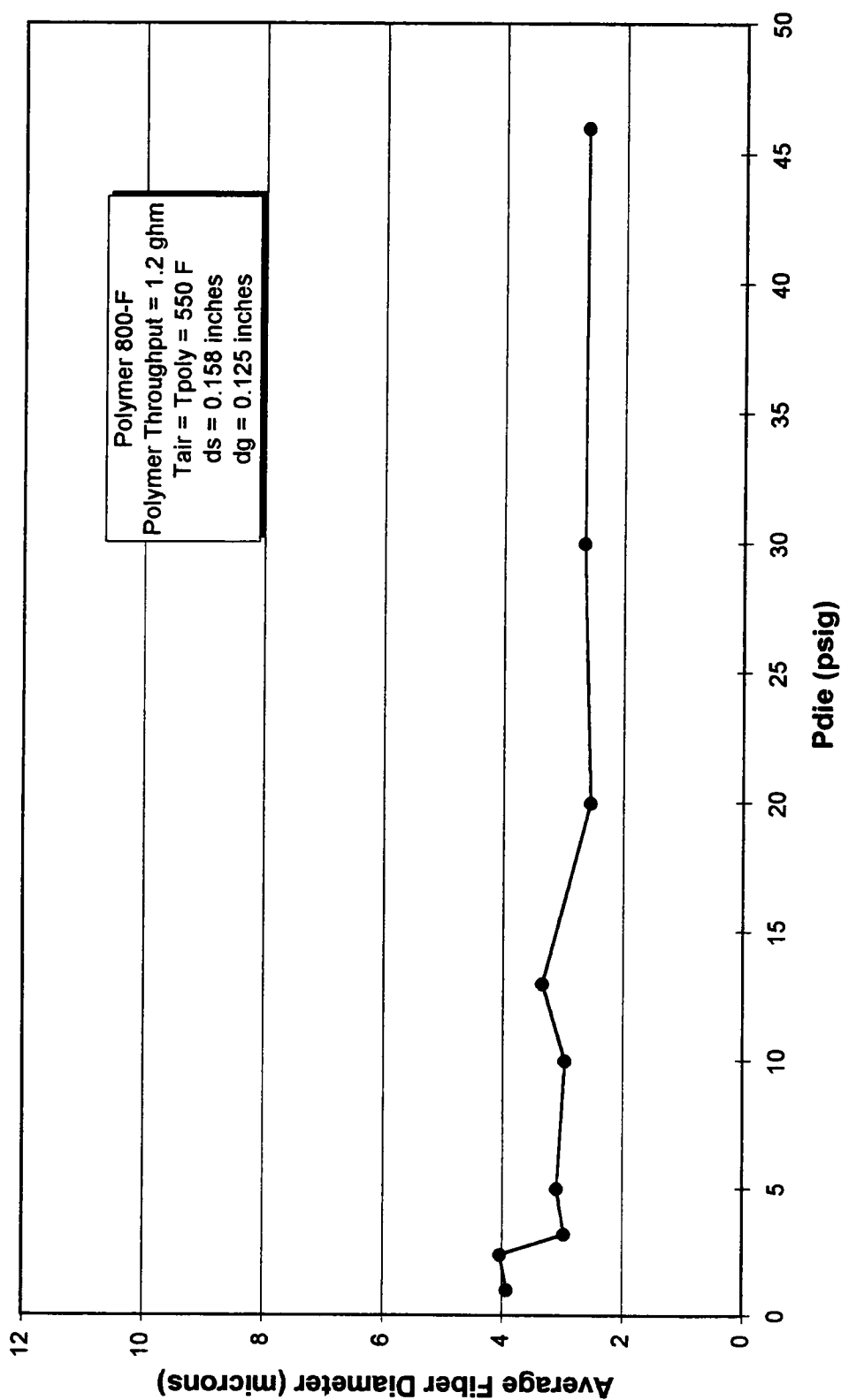


Figure 6.42: Average fiber diameter results obtained using the modified downstream converging - diverging nozzle configuration (ds = 0.158 inches, dg = 0.125 inches), for air and polymer temperatures of 550 degrees Fahrenheit.

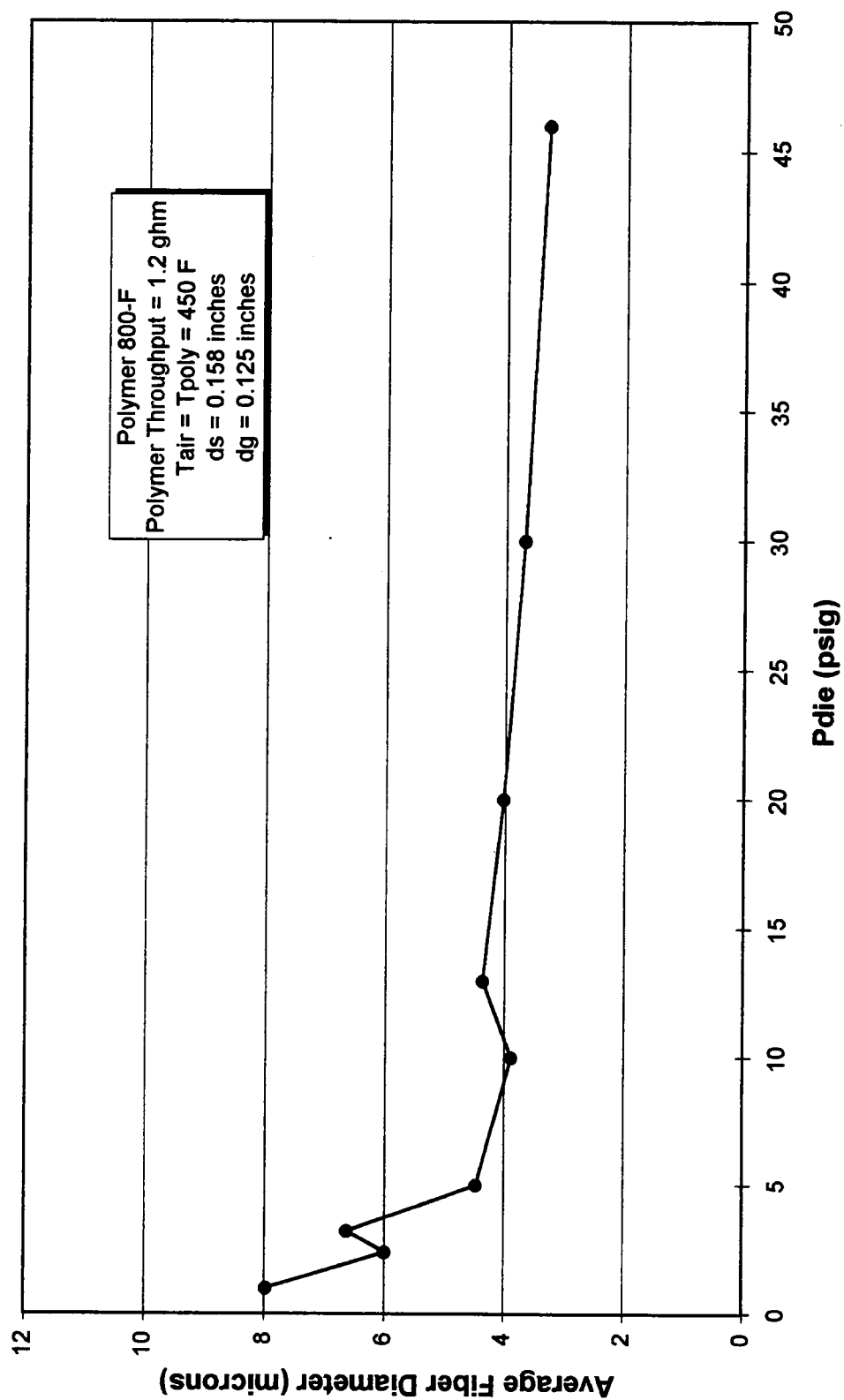


Figure 6.43: Average fiber diameter results obtained using the modified downstream converging - diverging nozzle configuration ($d_s = 0.158\text{ inches}$, $d_g = 0.125\text{ inches}$), for air and polymer temperatures of 450 degrees Fahrenheit.

Single Hole Die

To investigate the effect that decreasing the number of fibers being extruded had on the average fiber diameter, the multi-hole die was removed and replaced with the single hole. Die setback and air gap were kept at a constant 0.079 inches. Figures 6.44 and 6.45 show results pertaining to air and polymer temperatures of both 450 and 550 degrees Fahrenheit. For the higher polymer temperature of 550 degrees Fahrenheit shown in Figure 6.44, the average fiber diameters asymptotically approach an approximate value of 2.5 microns. This result is very close to the result found for the multi-hole case. Looking at Figure 6.45, the cooler polymer temperature of 450 degrees Fahrenheit, approaches an approximate value of 3 microns, about 1 micron smaller than what was found for the multi-hole case.

Therefore, the findings of both multi- and single hole die configurations, using the modified downstream c-d nozzle, support those found earlier in the chapter for the unmodified downstream c-d nozzle; i.e., average fiber diameter values tend to approach an asymptotic value that is dependent upon the polymer temperature.

Upstream Converging - Diverging Nozzle

The results obtained for the upstream c-d nozzle using both a multi- and single hole die are described in the following two sections. In Chapter V, it was mentioned that the main advantage of this type of nozzle was the exiting of the polymer fibers into an already existing supersonic flowfield.

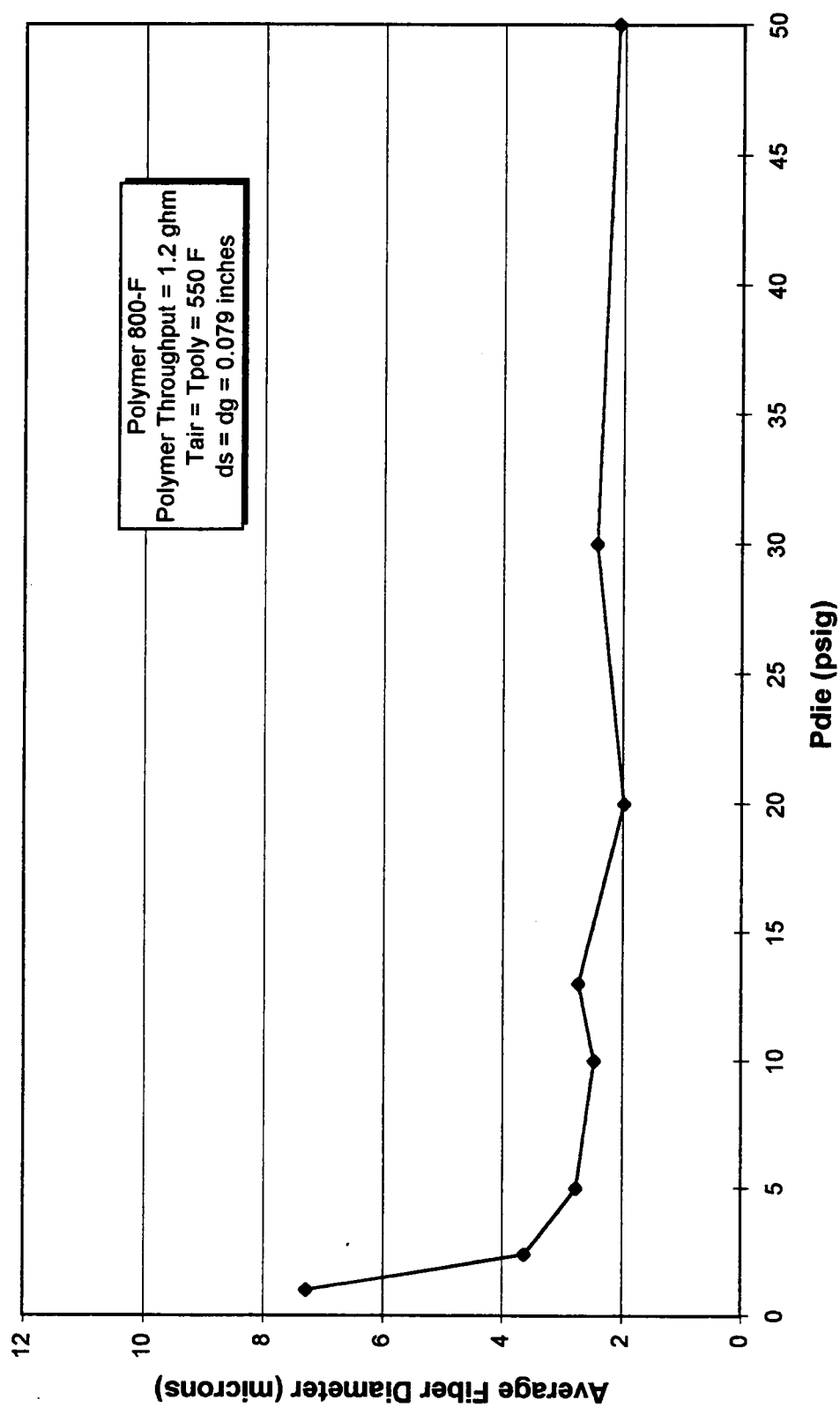


Figure 6.44: Average fiber diameter results obtained using a single hole die and modified downstream converging - diverging nozzle configuration ($ds = dg = 0.079\text{ inches}$), for air and polymer temperatures of 550 degrees Fahrenheit.

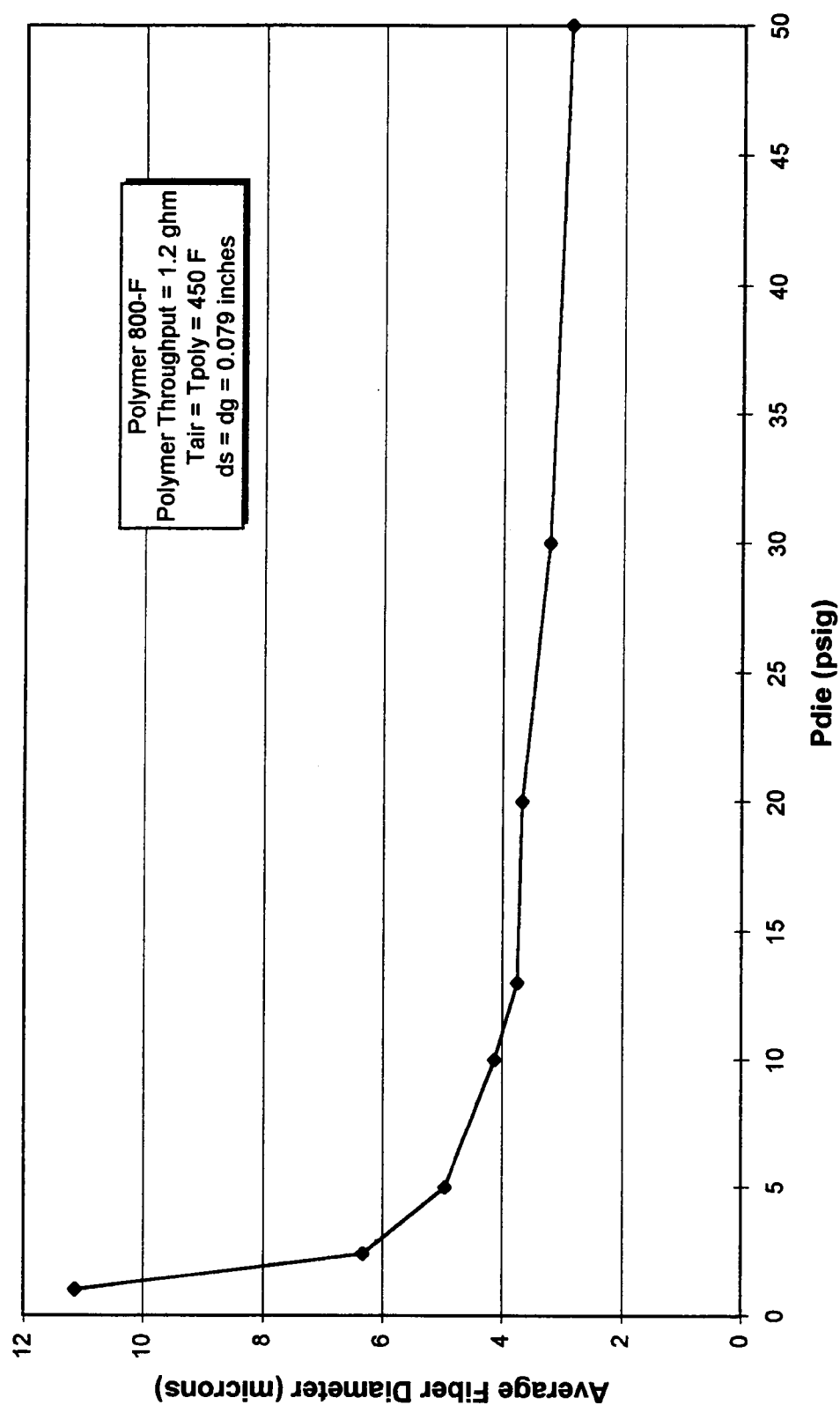


Figure 6.45: Average fiber diameter results obtained using a single hole die and modified downstream converging - diverging nozzle configuration ($ds = dg = 0.079$ inches), for air and polymer temperatures of 450 degrees Fahrenheit.

Multi-Hole Die

The die setback and air gap (throat height) for this configuration was set at 0.079 and 0.004 inches, respectively. As in both of the previous type of nozzle configurations, a shadowgraph was performed on the nozzle exiting flowfield to determine if supersonic flow had been achieved. The results of this technique showed that the diamonds (crows foot) would grow as the die stagnation pressure was increased. This growing effect is illustrated in Figure 6.46, with the highest stagnation pressure being represented by the third drawing. These diamonds were observed to appear at a stagnation pressure of 20 pounds per square inch gage. Having examined the flowfield through shadowgraph techniques, it was decided to try and determine what the approximate Mach number at the nozzle exit plane was. To do this, a setup similar to Figure 4.3 was used to measure the stagnation pressure at the nozzle exit. Using this pressure and assuming a normal shock wave was in front of the 90 degree pitot tube, Mach numbers and velocities relating to each pressure measured were calculated using the normal shock tables and isentropic flow tables found in John [17]. Figure 6.47 shows a plot of the pressure measured with the pitot tube compared to the die stagnation pressure. Figure 6.48 is a plot of Mach number versus the die stagnation pressure. According to this graph, the Mach number at the exit reached an approximate high value of 1.25. Using the temperatures measured at the die and assuming isentropic flow, the velocity was then calculated from the Mach numbers using the following equation:

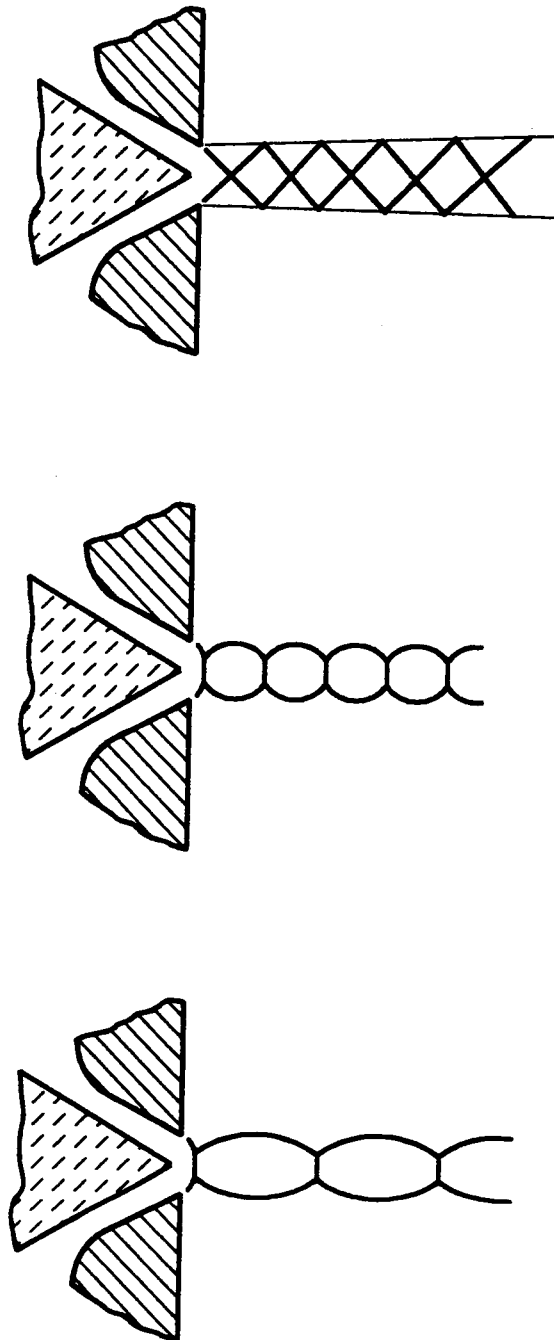


Figure 6.46: Shadowgraph observations for the upstream converging - diverging nozzle.

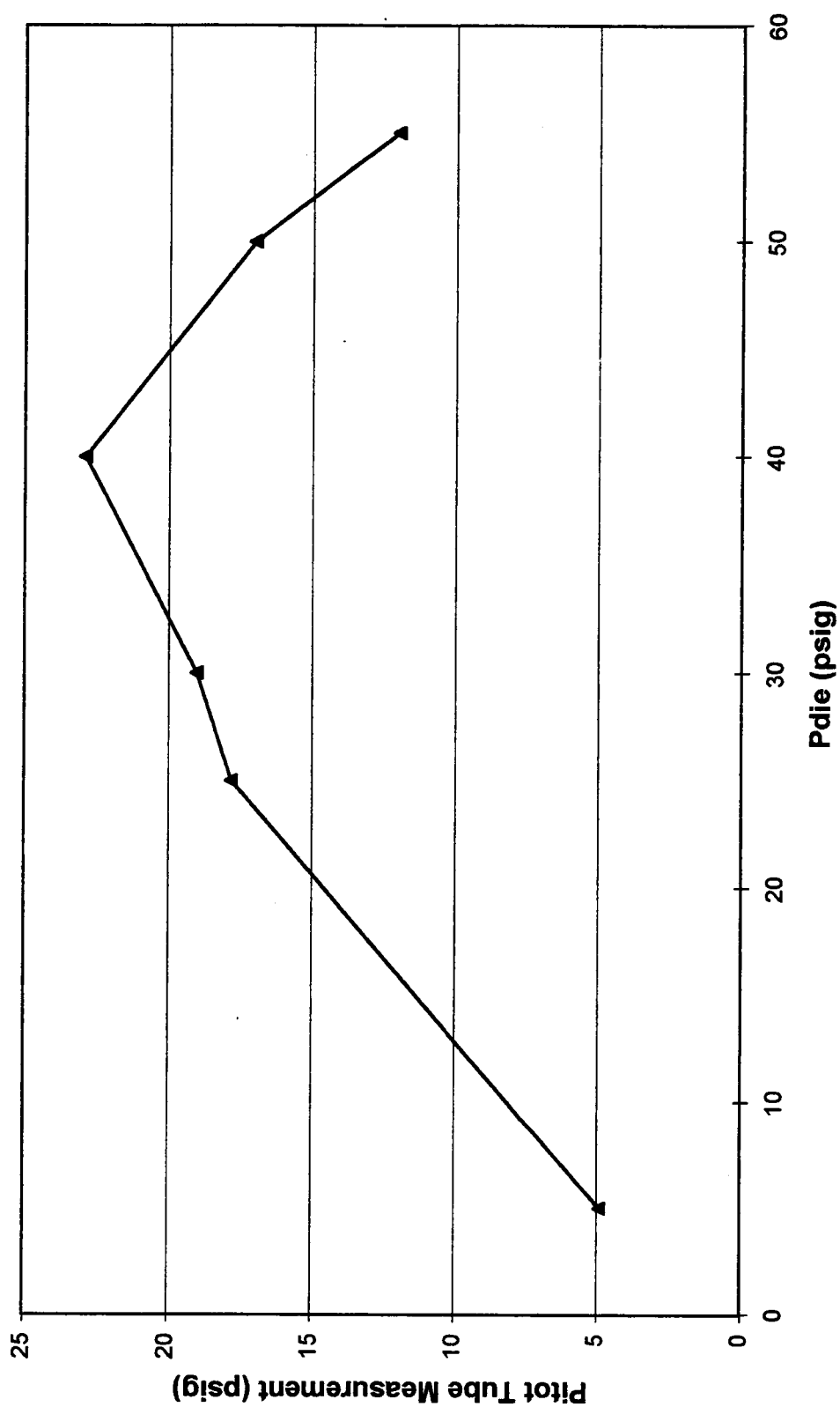


Figure 6.47: Pitot pressure measurements as related to die stagnation pressure for the upstream converging - diverging nozzle.

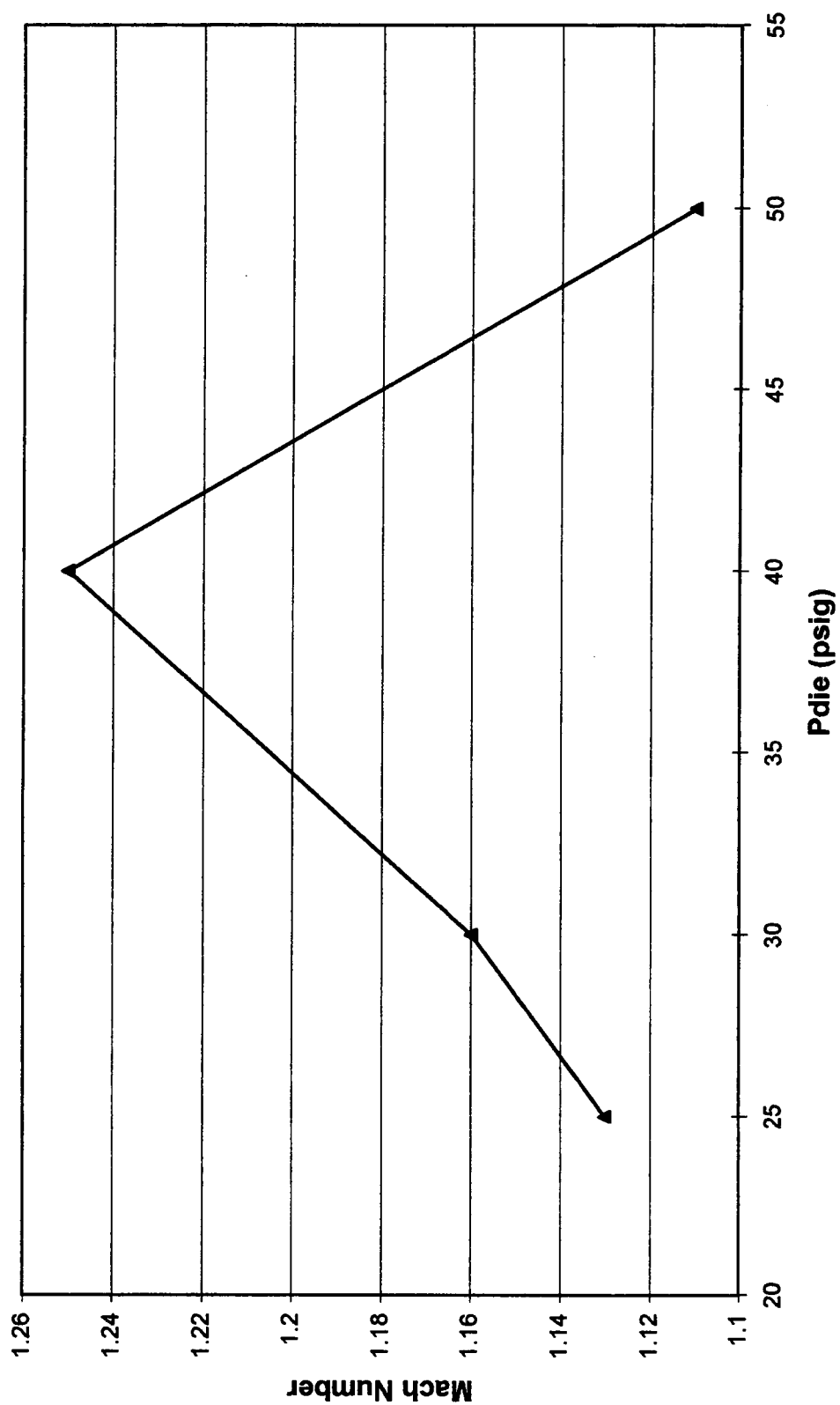


Figure 6.48: Mach number as related to die stagnation pressure for the upstream converging - diverging nozzle.

$$V_e = M_e \sqrt{\gamma R T_e} \quad 6.1$$

where,	V_e	velocity at the nozzle exit (m/s)
	M_e	Mach number at the nozzle exit
	γ	1.4 for air
	R	0.287 (KJ/kg-K)
	T_e	Temperature at the nozzle exit (K)

The results of this calculation are shown in Figure 6.49. Unlike the fiber behavior characteristics that were observed for the downstream c-d nozzle investigations, for the upstream case, no polymer was observed striking or dripping from any portion of the face plates that made up the divergent section of the nozzle. However, fiber-to-fiber collisions could still be seen. Examining the results found in Figures 6.50 and 6.51 for fiber diameter measurements, the values once again approached asymptotic values of 2.5 and 3 microns for polymer temperatures of 550 and 450 degrees Fahrenheit, respectively. These findings are identical to those found in the multi-hole modified c-d nozzle investigation. Based on this, a decision was made to perform another test at a higher polymer temperature to determine if there was an apparent limit on the asymptotic value. The results of this test are shown in Figure 6.52. As can be seen in this figure, the fiber diameter values only decreased by an amount of 0.22 microns over the entire die stagnation pressure range. This suggests that at this polymer temperature, the value asymptotically approached a

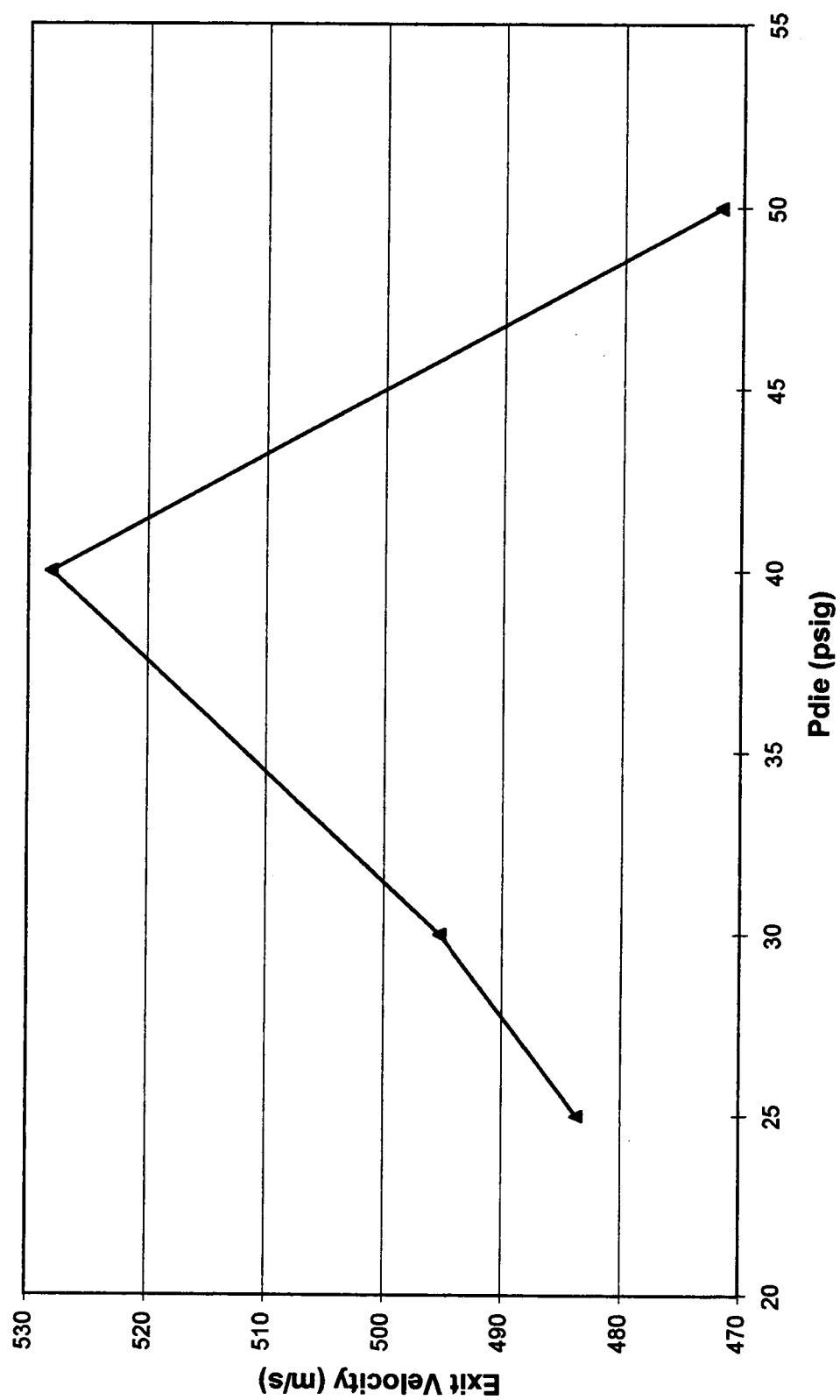


Figure 6.49: Air exit velocity as related to die stagnation pressure for the upstream converging - diverging nozzle.

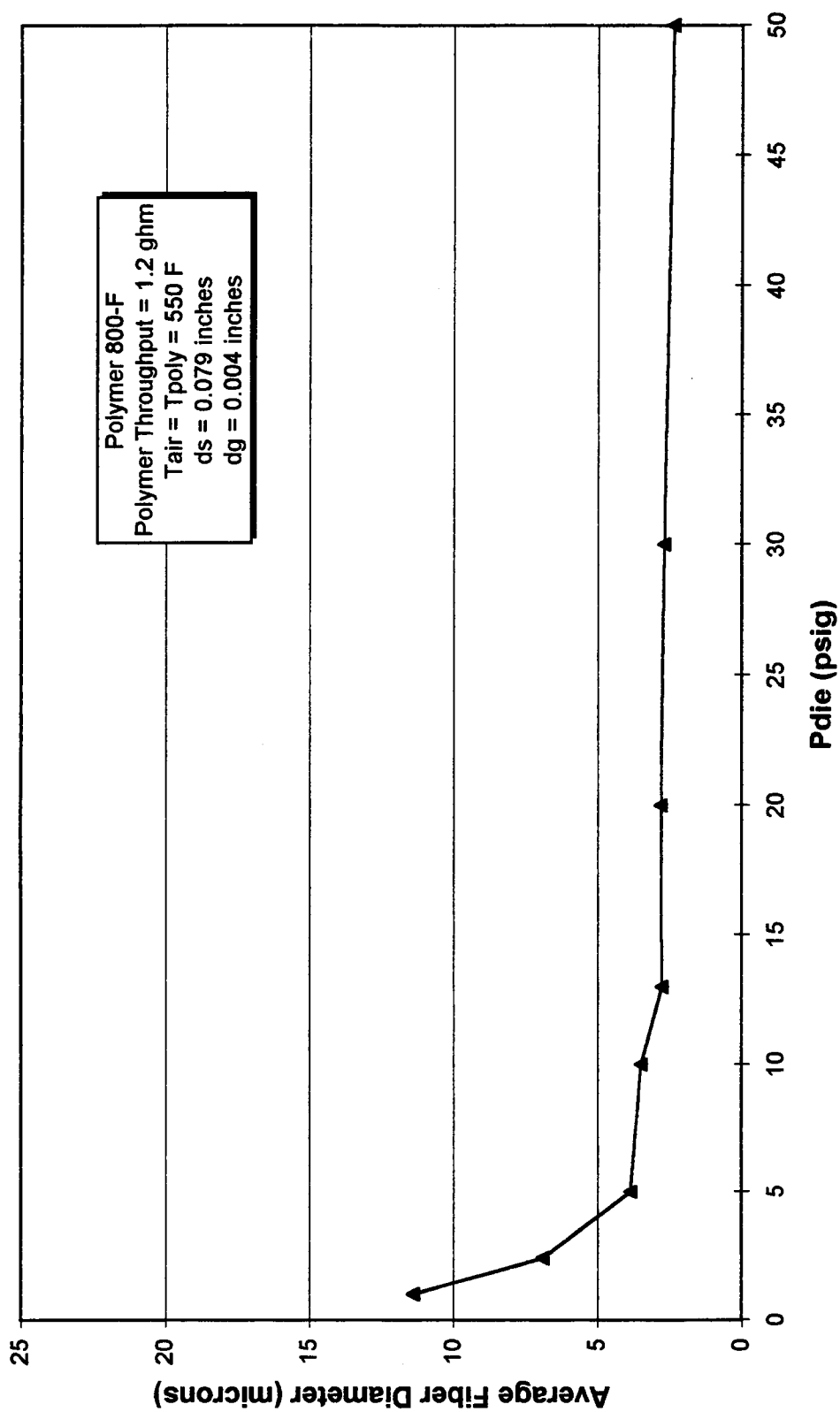


Figure 6.50: Average fiber diameter results obtained using the upstream converging - diverging nozzle configuration ($d_s = 0.079$ inches, $d_g = 0.004$ inches), for air and polymer temperatures of 550 degrees Fahrenheit.

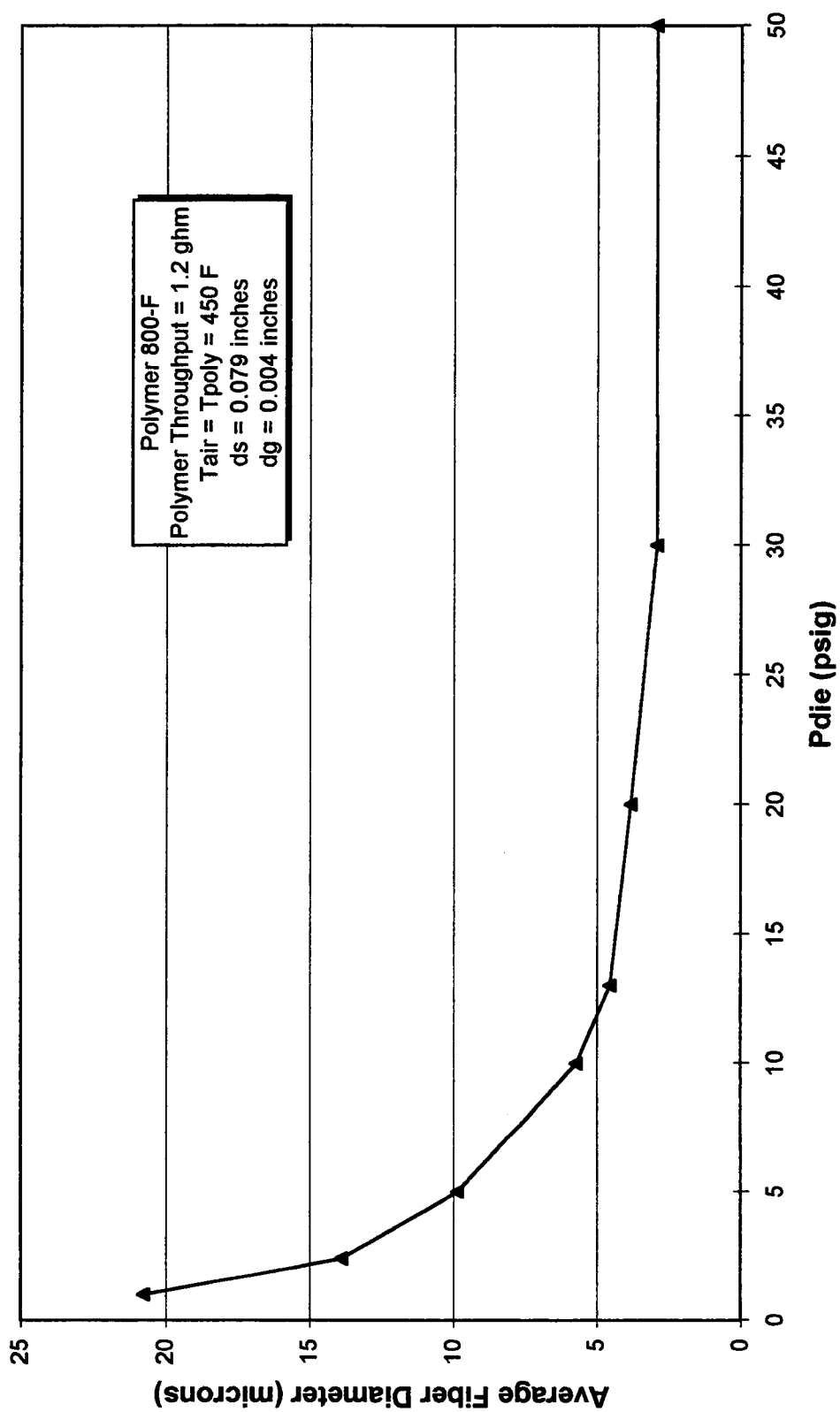


Figure 6.51: Average fiber diameter results obtained using the upstream converging - diverging nozzle configuration (ds = 0.079 inches, dg = 0.004 inches), for air and polymer temperatures of 450 degrees Fahrenheit.

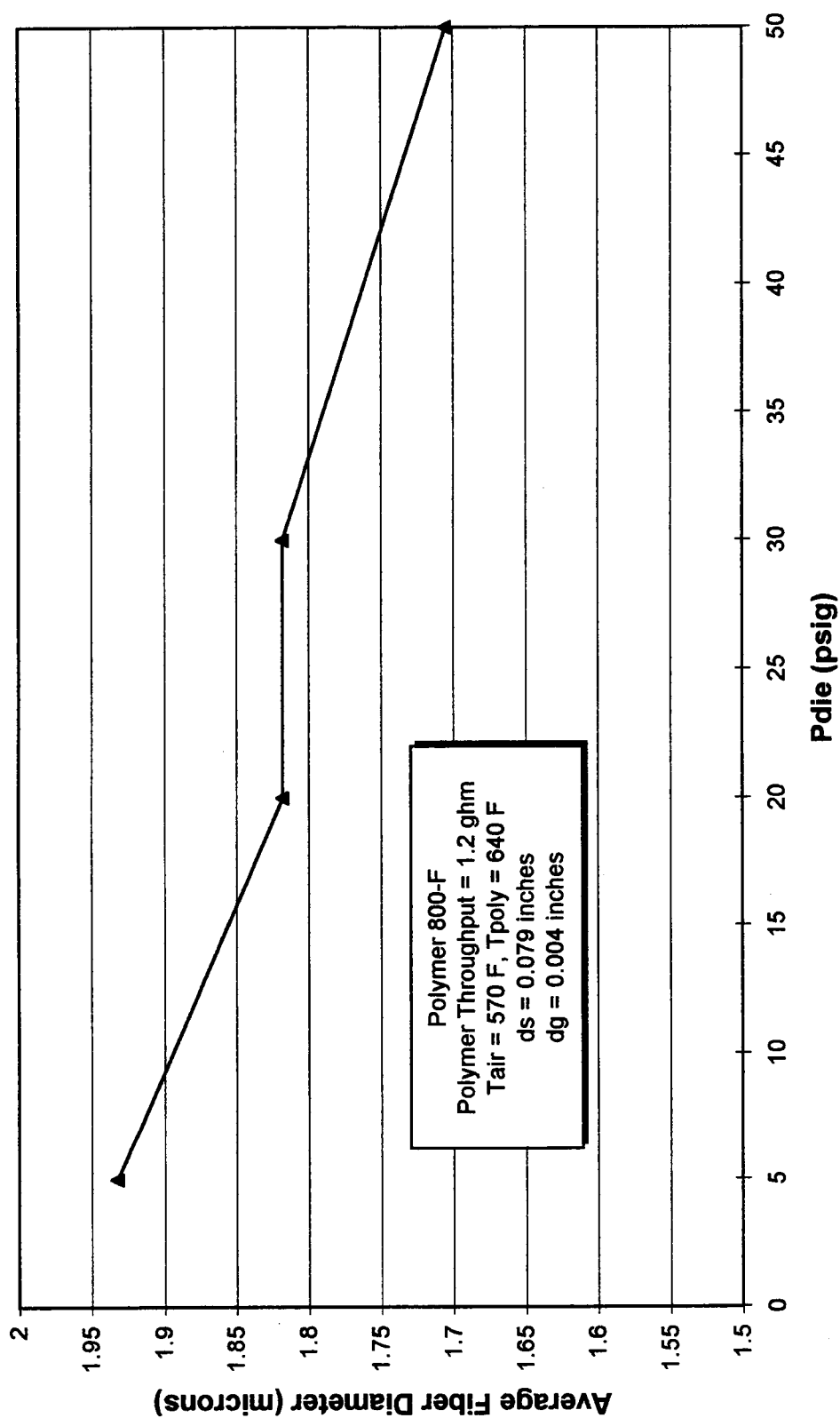


Figure 6.52: Average fiber diameter results obtained using the upstream converging - diverging nozzle configuration (ds = 0.079 inches, dg = 0.004 inches), for an air temperature of 570 degrees Fahrenheit and a polymer temperature of 640 degrees Fahrenheit.

fiber diameter value of 1.8 microns. It should be noted however, since the fiber diameters being measured were less than 2 microns and the least count of the optical microscope is 2.5 microns, the results obtained for this one study become fairly dependent upon the judgment of the person performing the data reduction.

Single Hole Die

Figure 6.53 shows the average fiber diameters for the single hole configuration, at a polymer and air temperature of 550 degrees Fahrenheit, decreasing to an asymptotic value of 1.8 microns, slightly smaller than the 2.5 microns found for the multi-hole configuration. For a polymer and air temperature of 450 degrees Fahrenheit, shown in Figure 6.54, the average fiber diameters asymptotically approach a value of 3 micron; which is identical to the value found in the multi-hole investigation.

The findings of this investigation also support the conclusions of one asymptotic value, for a given polymer temperature, found for both configurations of downstream c-d nozzles (multi- and single hole cases).

Electron Microscope Verification of Fiber Diameters

As was mentioned earlier, the least count of the optical microscope was 2.5 microns. With fiber diameters being measured approaching values smaller than the least count, it was decided that SEM measurements should be obtained and compared to optical microscope measurements, for some of the samples collected using the three different c-d

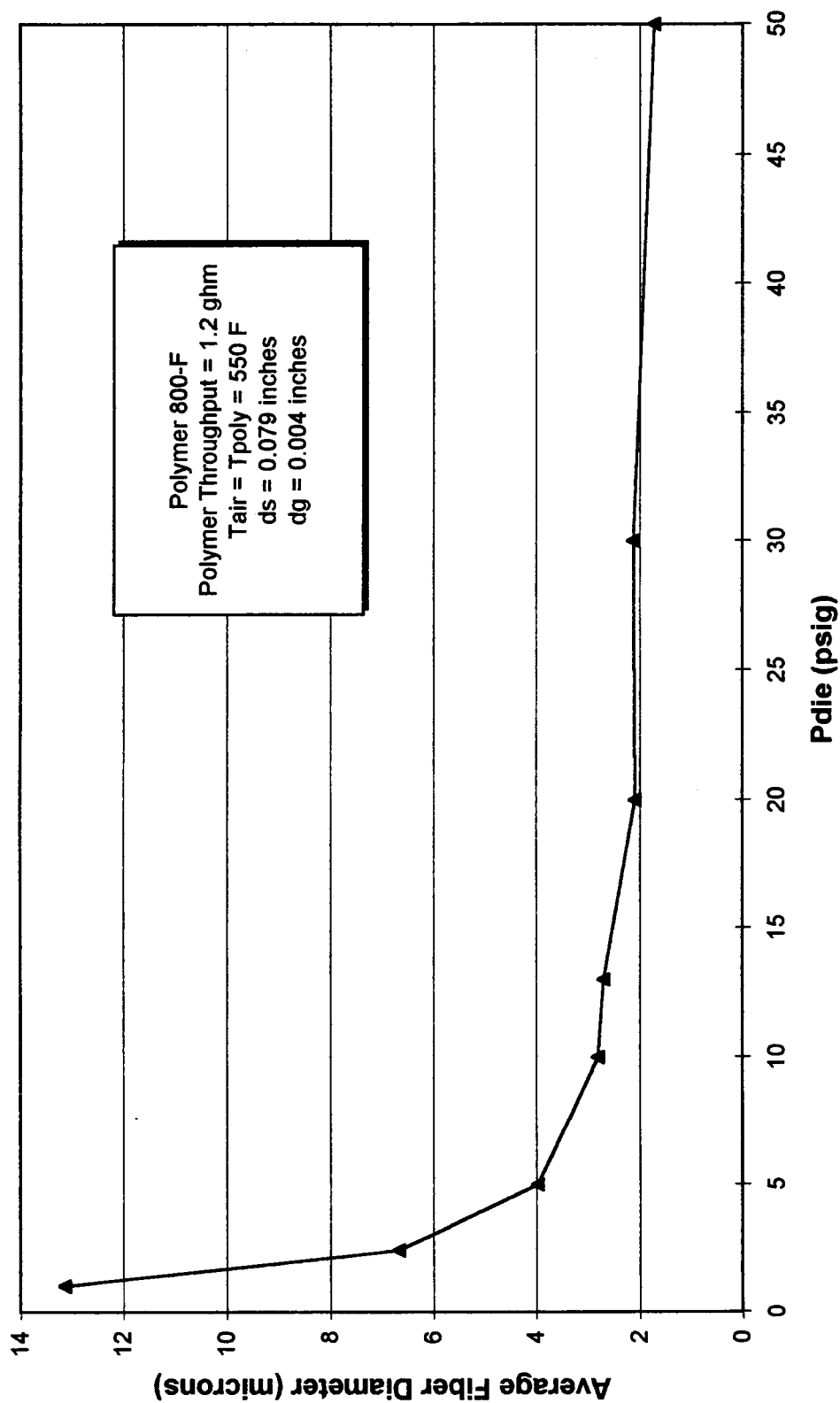


Figure 6.53: Average fiber diameter results obtained using a single hole die and upstream converging - diverging nozzle configuration (ds = 0.079 inches, dg = 0.004 inches), for air and polymer temperatures of 550 degrees Fahrenheit.

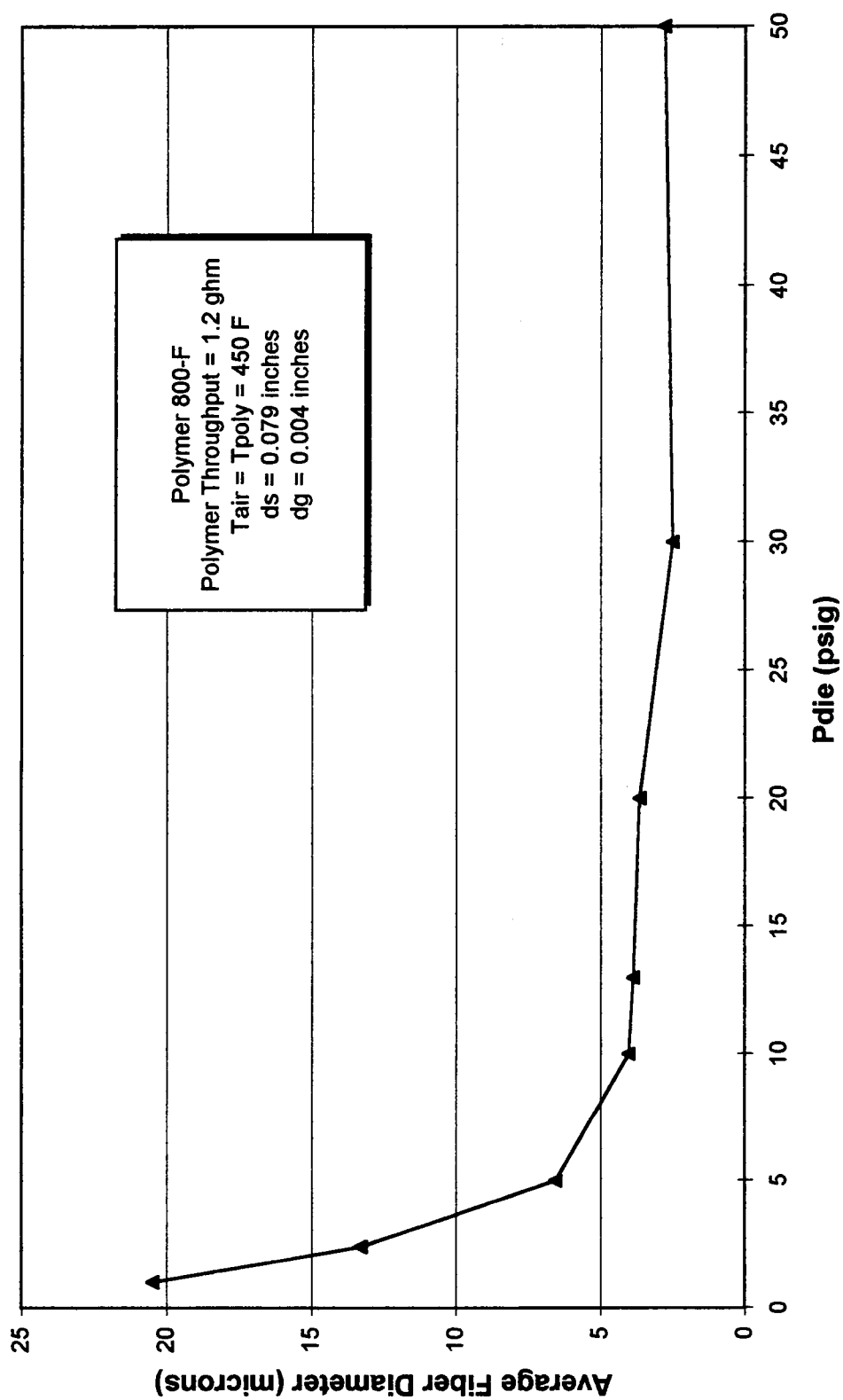


Figure 6.54: Average fiber diameter results obtained using a single hole die and upstream converging - diverging nozzle configuration (ds = 0.079 inches, dg = 0.004 inches), for air and polymer temperatures of 450 degrees Fahrenheit.

nozzle configurations. Typical SEM photographs can be seen in Figures 6.55 through 6.57. Figure 6.55 is a SEM photograph of a web collected using the downstream c-d nozzle at air and polymer temperatures of 450 degrees Fahrenheit, polymer throughput of 1.2 grams/minute per hole, and a die stagnation pressure of 56 pounds per square inch gage. A sample collected using the modified c-d nozzle can be seen in Figure 6.56. This sample was collected at an air and polymer temperature of 550 degrees Fahrenheit with a die stagnation pressure of 46 pounds per square inch gage. Figure 6.57 is a photograph of fibers collected at a die stagnation pressure of 50 pounds per square inch gage with air and polymer temperatures at 450 degrees Fahrenheit. A comparison of optical versus SEM is given with percent difference in Table 6.10. One of the limitations associated with the use of an SEM technique is the size of the area examined. Due to the larger fiber diameters associated with shot, if a shot particle happens to be near an area photographed for SEM measurements, the fiber diameter results can be skewed and will not be representative of the web sample.

Comparison of Nozzle Configurations

The average fiber diameter results obtained using both the multi-hole modified and upstream c-d nozzles (at $T_{air} = T_{poly} = 550$ degrees Fahrenheit) has already been shown to asymptotically approach a value between 2 and 4 microns. In this section, a comparison between the results obtained using these two c-d nozzles and those obtained using the typical melt blowing converging nozzle configuration described in Chapter II will be made.

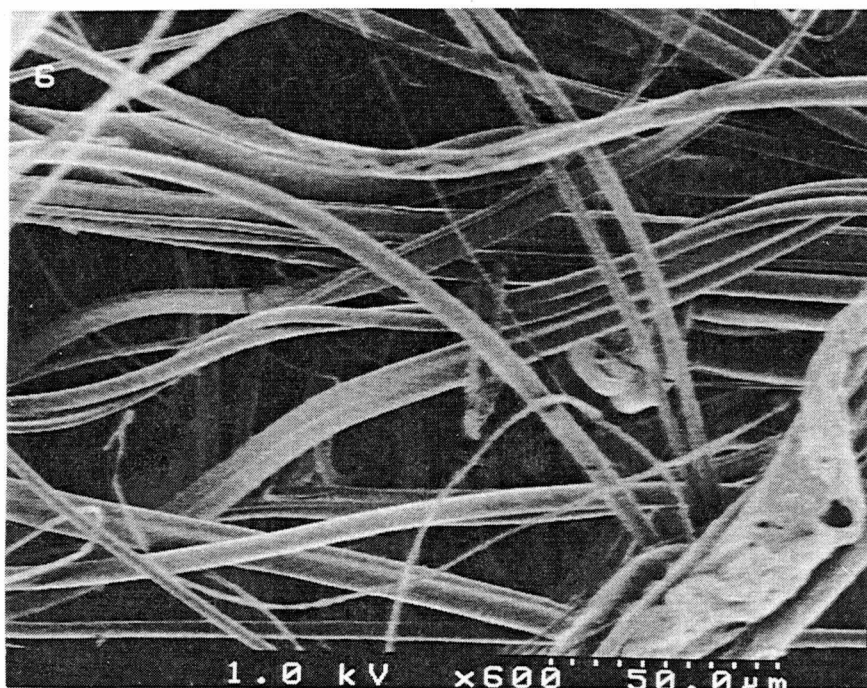


Figure 6.55: SEM photograph of downstream c-d nozzle fibers for a die stagnation pressure of 56 psig. $d_s = d_g = 0.079$ inches. $T_{air} = T_{poly} = 450$ °F.

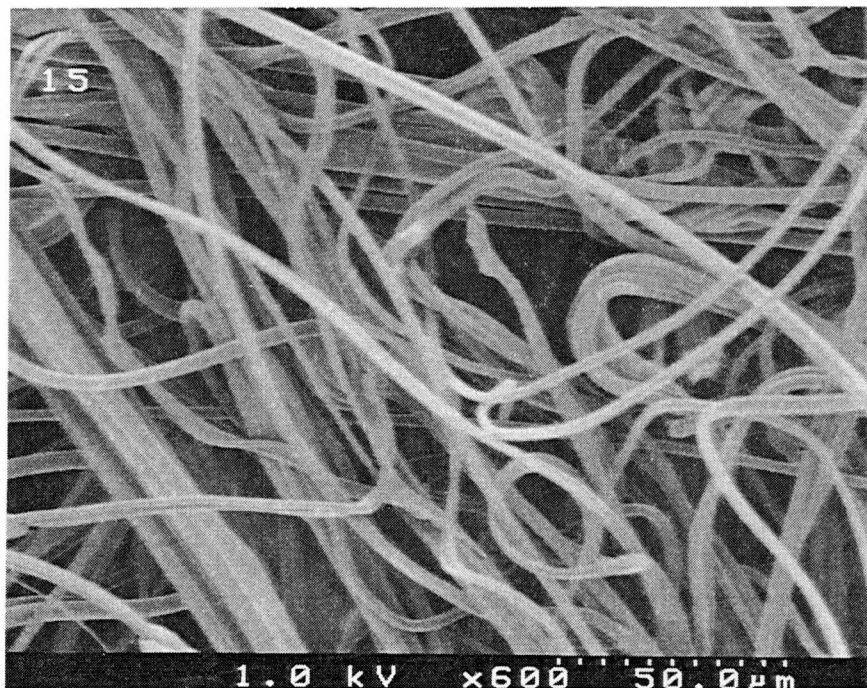


Figure 6.56: SEM photograph of modified downstream c-d nozzle fibers for a die stagnation pressure of 46 psig. $d_s = 0.158$ inches, $d_g = 0.125$ inches. $T_{air} = T_{poly} = 550$ °F.

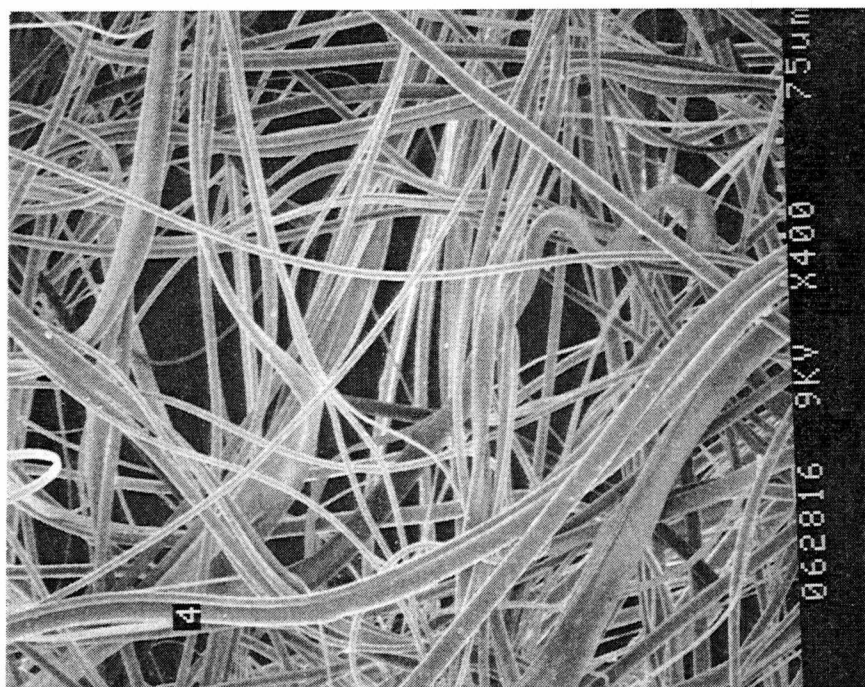


Figure 6.57: SEM photograph of upstream c-d nozzle fibers for a die stagnation pressure of 50 psig. $d_s = 0.079$ inches, $d_g = 0.04$ inches. $T_{air} = T_{poly} = 450$ °F.

Table 6.10: Comparison of optical microscope measurements to measurements obtained from SEM.

Nozzle Type	Optical Diameter (microns)	SEM Diameter (microns)	% Difference
Converging:			
	2.96	3.13	5.58
	3.94	4.77	19.06
Downstream C-D:			
	5.22	4.39	-17.27
	3.45	3.79	9.39
	3.18	3.77	16.98
	3.40	4.57	29.36
Modified Downstream C-D:			
	5.38	5.77	7.00
	3.98	3.69	-7.56
	2.74	2.77	1.09
	2.73	3.17	14.92
	2.77	2.49	-10.64
	3.91	4.08	4.25
	3.08	3.26	5.68
	2.66	3.52	27.83
	2.62	2.77	5.57
	7.97	10.39	26.36
	4.46	5.14	14.17
	3.67	3.75	2.16
	3.30	4.27	25.63
Upstream C-D:			
	2.12	4.14	64.54
	1.71	3.14	58.97
	2.50	5.14	69.11
	2.80	4.82	53.02

A plot of average fiber diameter versus die stagnation pressure for both the modified downstream c-d ($d_s = d_g = 0.079$ inches) and the typical melt blowing configuration is shown in Figure 6.58. As can be seen from this figure, over the same pressure range, the fiber diameters of the modified nozzle were found to be much smaller than those of the typical melt blowing nozzle configuration. This was also the case when the die setback and air gap was increased as shown in Figure 6.59. A comparison of results for the upstream nozzle is plotted in Figure 6.60. In this figure, the average fiber diameters were found to be only slightly smaller than the diameters obtained for the typical melt blowing converging nozzle configuration. As the die stagnation pressure was increased, the converging nozzle fiber diameter values appeared to asymptotically approach the upstream nozzle values. By plotting all four nozzle diameter measurement results onto one graph, this asymptotic trend, shown to occur for each nozzle configuration at a given polymer temperature previously in this chapter, can be seen more clearly. This graph is shown in Figure 6.61.

The findings of this comparison show that fiber diameters produced at low die stagnation pressures (subsonic flow conditions) using the modified downstream c-d nozzle configuration were much smaller than those produced using the typical melt blowing converging nozzle configuration. Also, for all c-d nozzle configurations examined, fiber diameters were found to approach an asymptotic value of approximately 2 microns as the die stagnation pressure was increased to supersonic flow conditions.

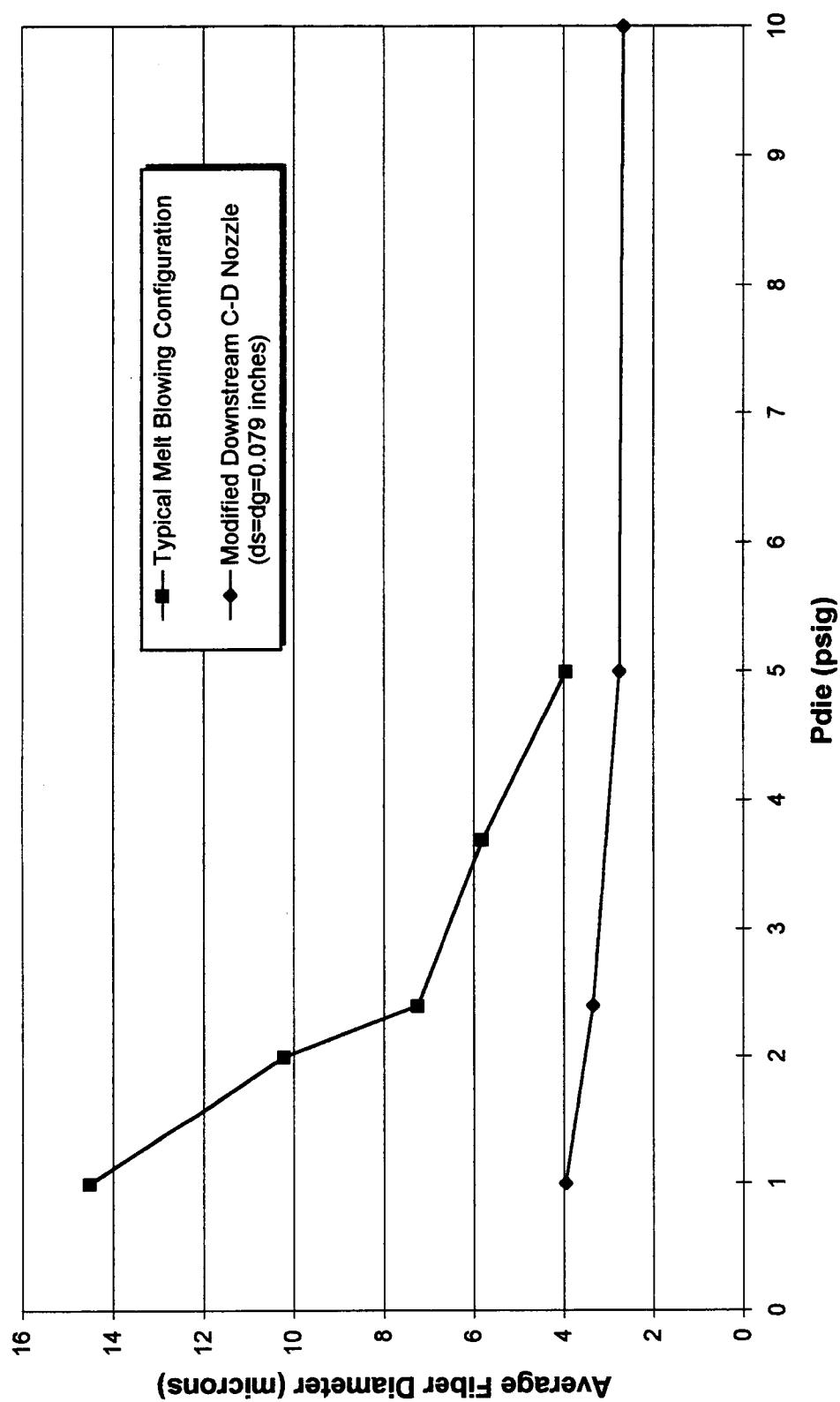


Figure 6.58: Comparison of average fiber diameter results obtained using the typical melt blowing configuration and the modified downstream converging - diverging nozzle configuration ($ds = dg = 0.079$ inches), for air and polymer temperatures of 550 degrees Fahrenheit.

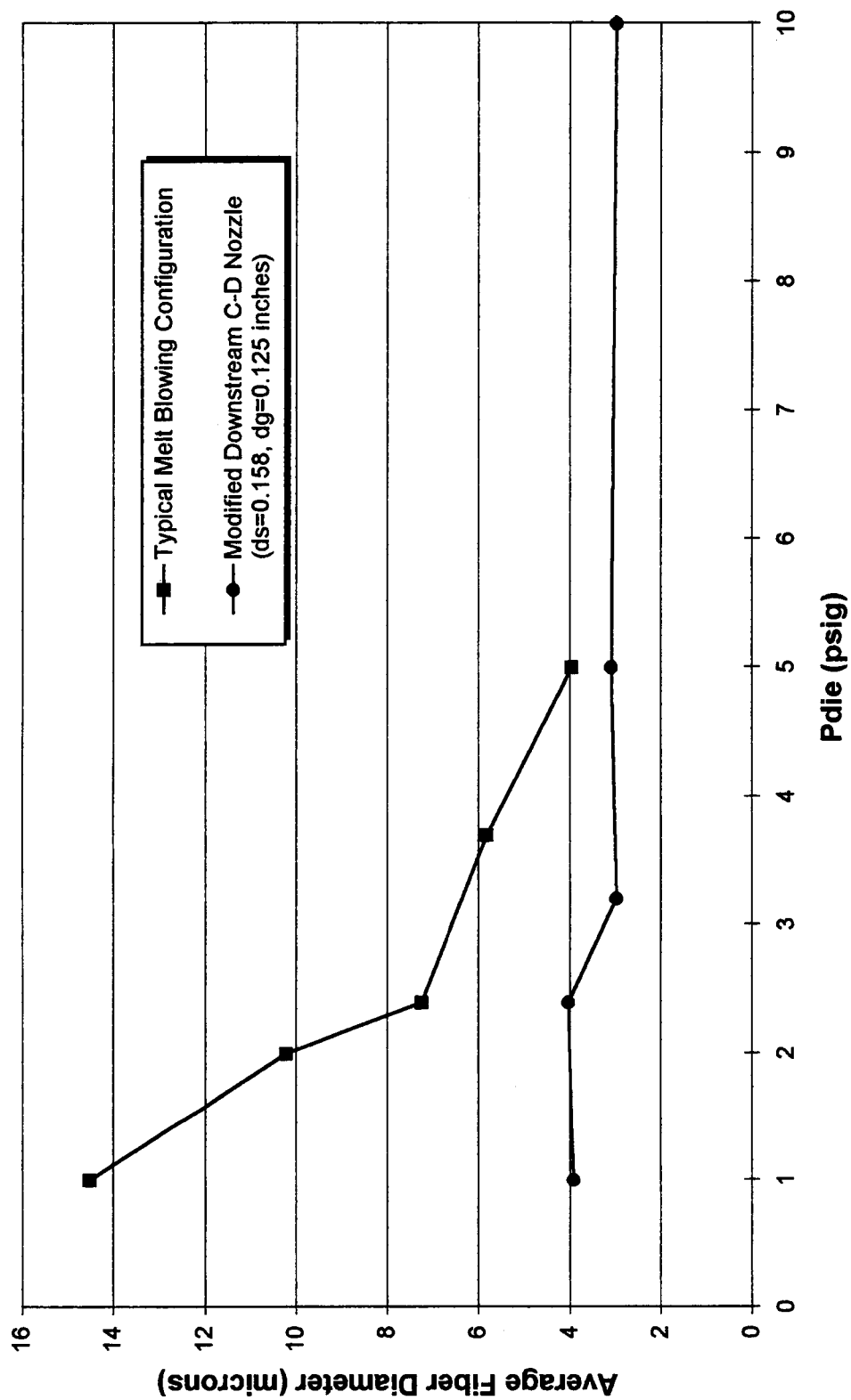


Figure 6.59: Comparison of average fiber diameter results obtained using the typical melt blowing configuration and the modified downstream converging - diverging nozzle configuration ($ds = 0.158$ inches, $dg = 0.125$ inches), for air and polymer temperatures of 550 degrees Fahrenheit.

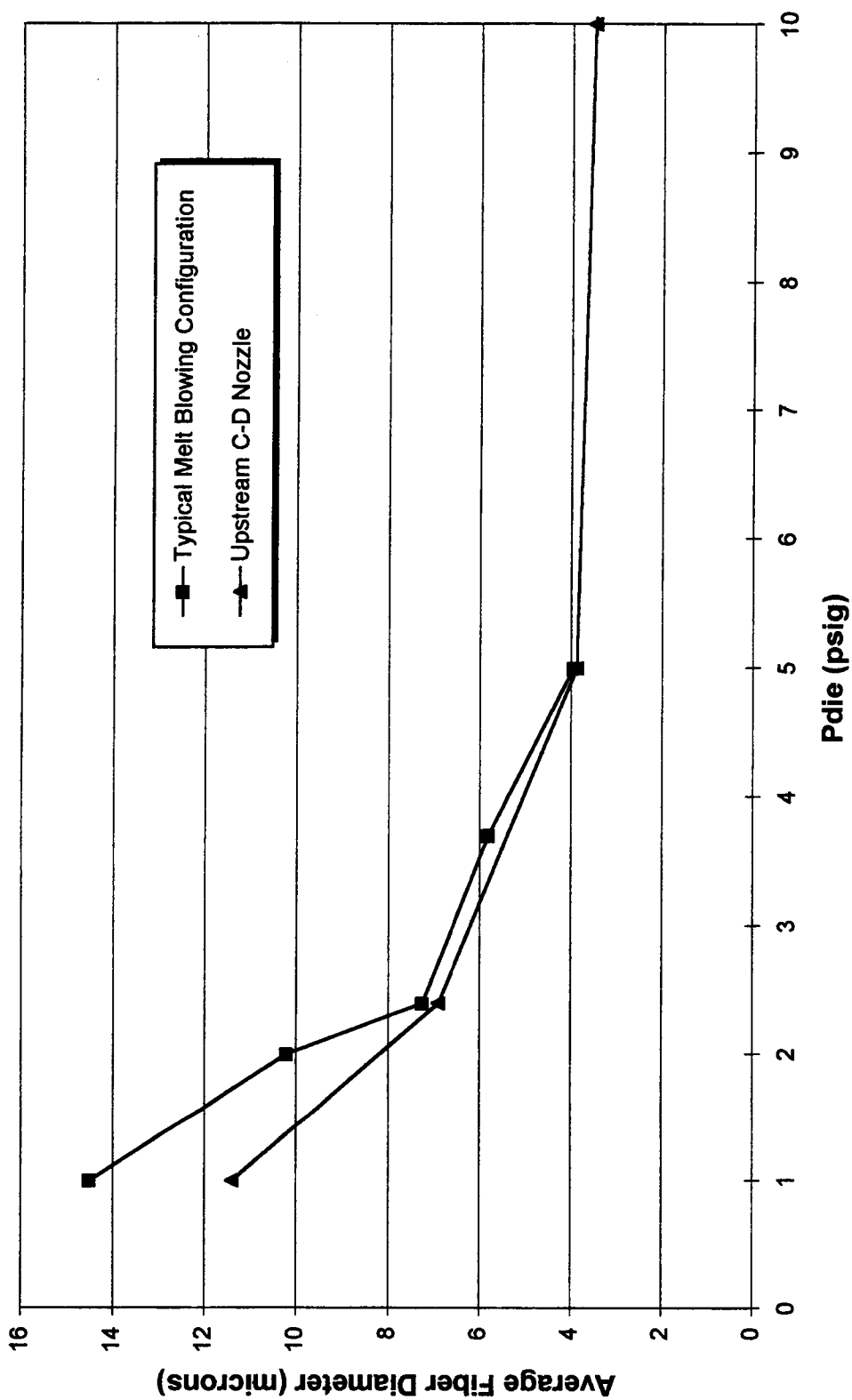


Figure 6.60: Comparison of average fiber diameter results obtained using the typical melt blowing configuration and the upstream converging - diverging nozzle configuration, for air and polymer temperatures of 550 degrees Fahrenheit.

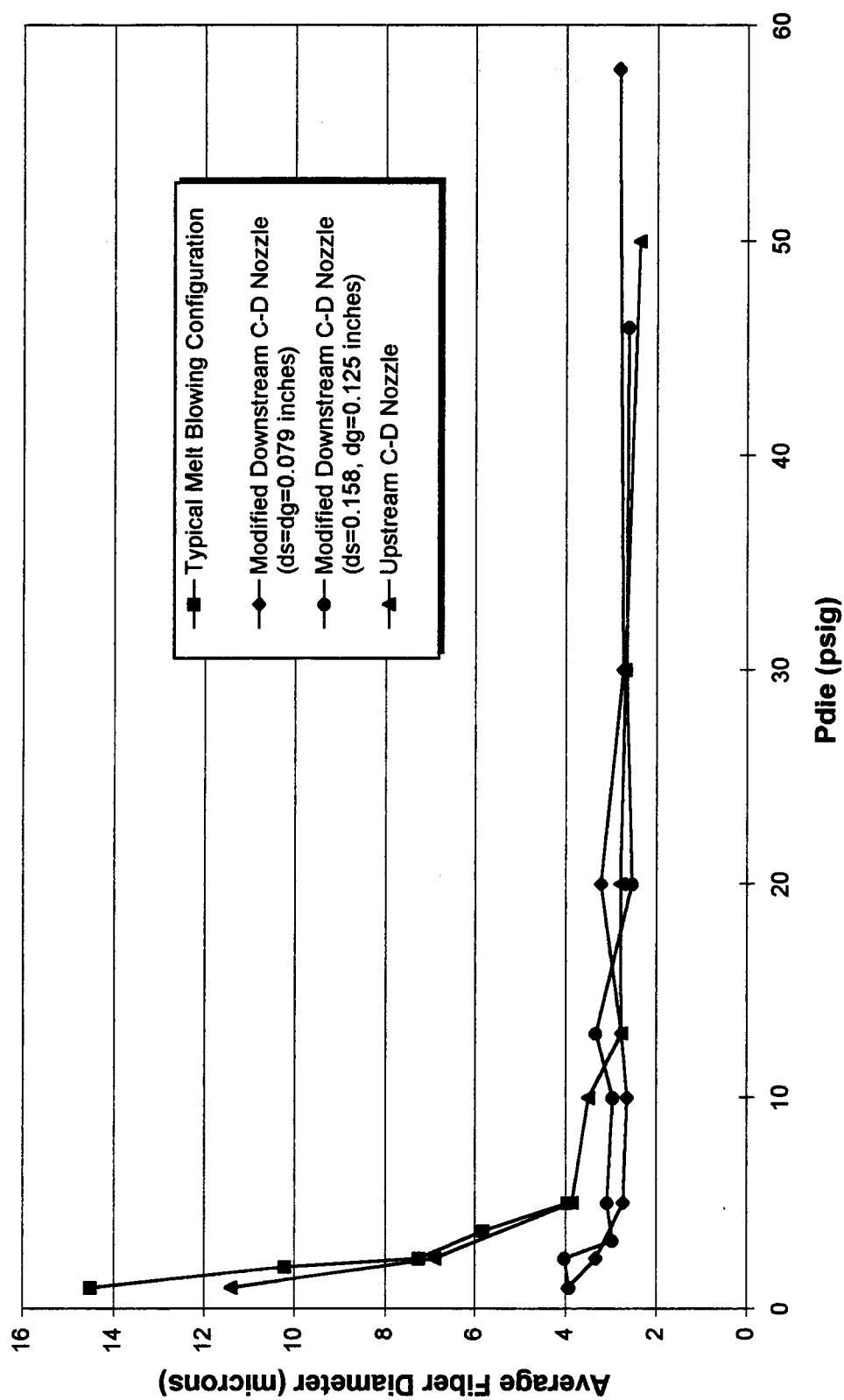


Figure 6.61: Comparison of average fiber diameter results obtained using all four nozzle configurations, for air and polymer temperatures of 550 degrees Fahrenheit.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

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

1. Using the conventional melt blowing configuration, average fiber diameters were found to decrease as the air exit velocity increased for all polymers investigated (MFR's between 400 and 1385).
2. Test results were found to be reproducible for the various MFR polymers investigated during this research.
3. For web samples less than 0.6 ounces per square yard in weight, the shot intensity scheme was found to be more quantitative and less subjective than the shot rating technique. A high degree of uncertainty is introduced for webs of greater weight per unit area.
4. Shot intensity values were found to decrease as the air exit velocity increased. In addition, these values were also found to decrease as the polymer temperature was decreased.

5. Average fiber diameters decreased with increasing polymer temperature. This was due to the longer attenuation times and the smaller die swell sizes associated with increased polymer temperature.
6. For the typical melt blowing nozzle configuration, extruded fibers are exposed to centerline air velocities that resemble the classical free jet flowfield as distance from the die exit plane increases.
7. Through the use of stop motion photography of multiple fibers in flight and high speed video of a single fiber in flight, it was concluded that the primary mechanism causing the production of shot was not the "snapping" back phenomenon reported by many researchers, but rather, the "touching" or colliding of molten fibers close to the die exit plane.
8. Two types of shot were identified, these were: (1) shot particle within the web resembling a film spot which showed signs of melting the adjacent fibers and (2) shot particle within the web showed no signs of web melting.
9. Using the downstream converging - diverging nozzle, molten fibers were found to collide with both the nozzle wall and with each other downstream of the nozzle throat, within the divergent section. These collisions were attributed to fiber motion due to the traversing of shock waves and/or the presence of separation regions inside the divergent section.
10. For low die stagnation pressures, webs produced using the downstream converging - diverging nozzles were found to contain fibers whose diameters were much smaller

than those obtained with the conventional melt blowing configuration.

11. Using both upstream and downstream converging - diverging nozzles, average fiber diameters for samples collected at polymer temperatures between 450 and 600 degrees Fahrenheit, were found to asymptotically approach a value between 1.8 and 4.5 microns with increasing die stagnation pressure. This asymptotic value was dependent upon the polymer temperature.

Recommendations

The following studies are recommended in order to better quantify the effects increased air exit velocity and fiber-to-fiber fusing have on web characteristics.

1. A wide range of polymer temperatures should be examined using the converging - diverging nozzle configuration in order to determine how dependent the fiber diameter asymptotic value is on this parameter.
2. To better understand fiber-to-fiber fusion, an empirical analysis should be undertaken in order to try and approximate at what distances from the die exit plane fibers begin to solidify.

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APPENDIX

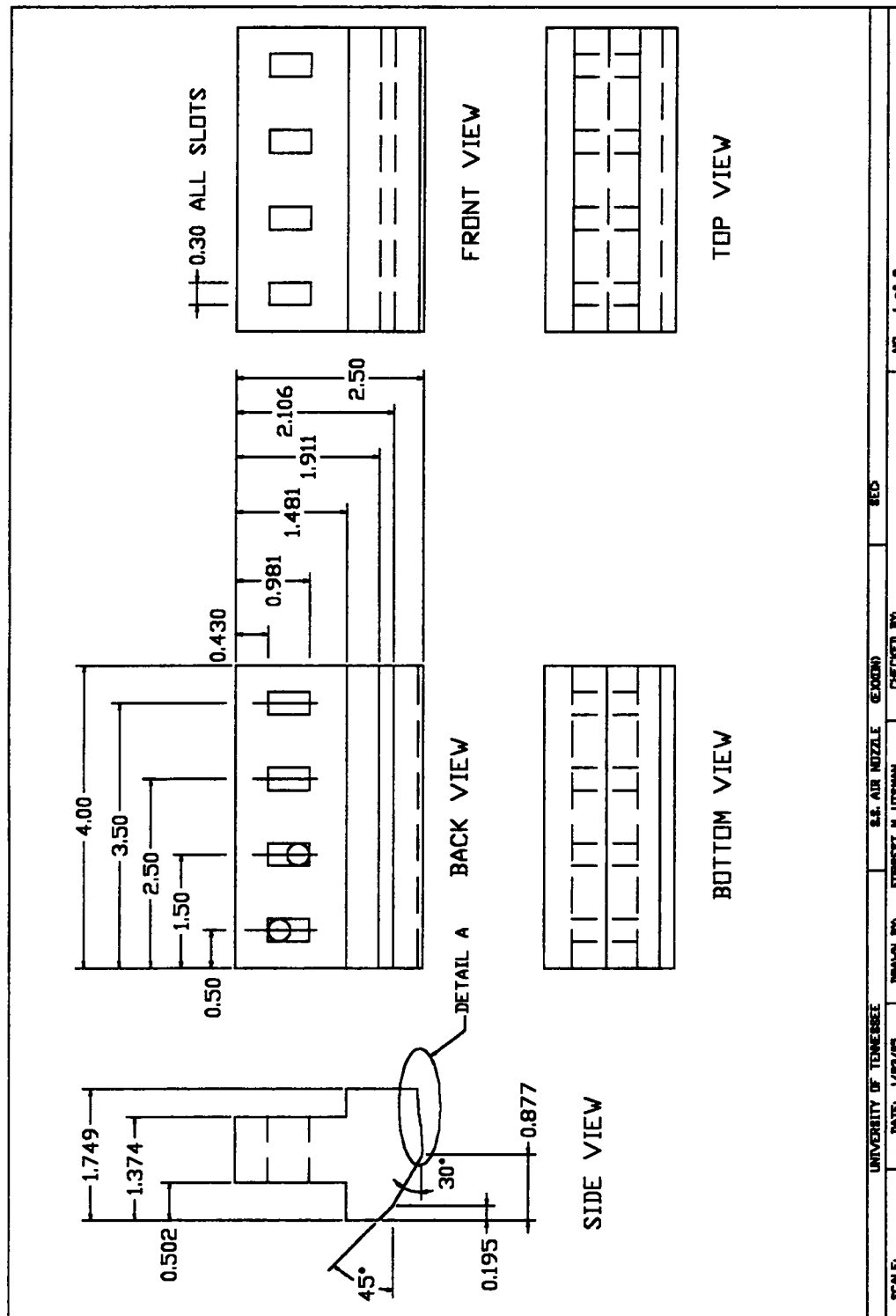


Figure A1: Drawing of downstream c-d nozzle.

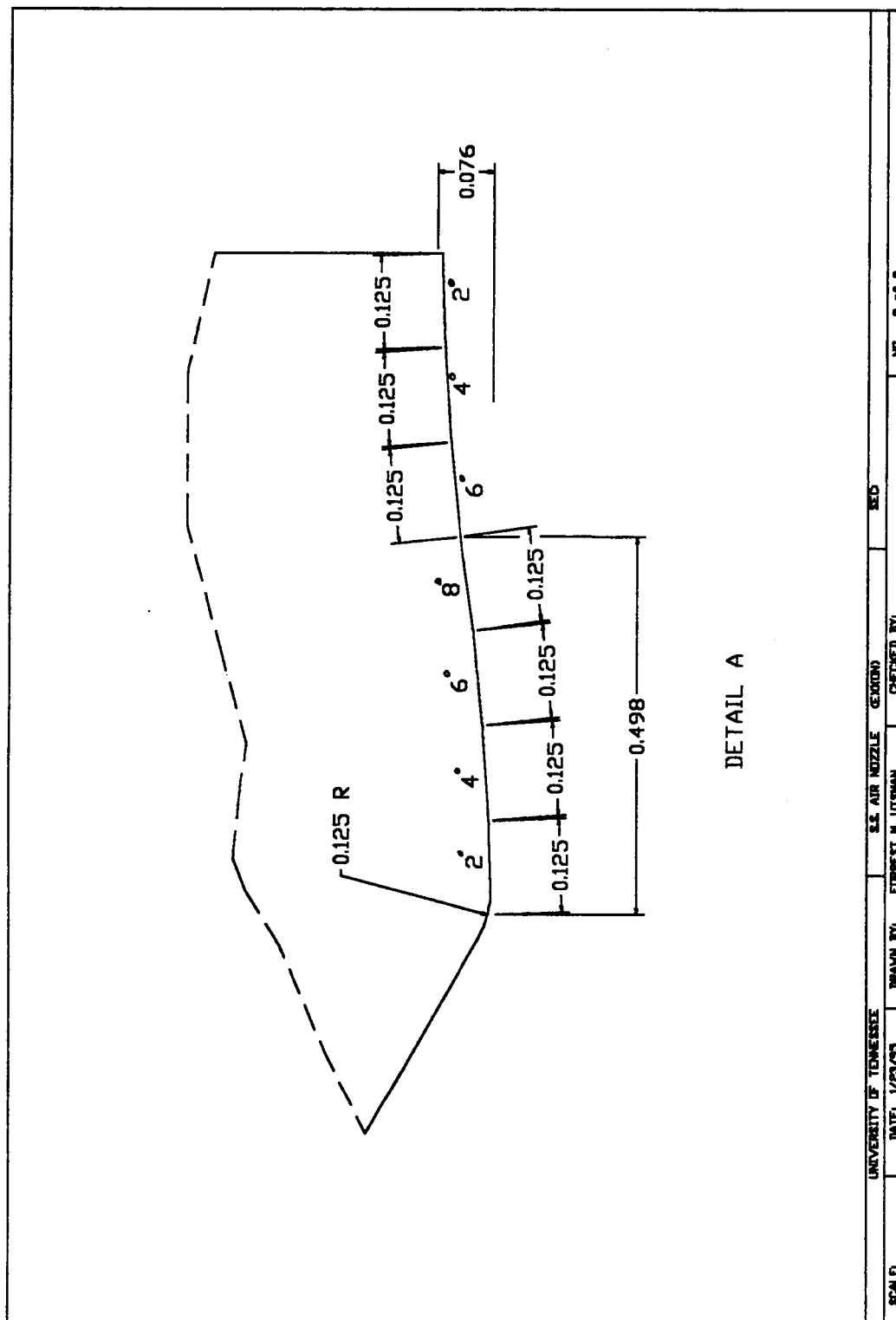


Figure A2: Drawing of downstream c-d nozzle divergent section wall contour.

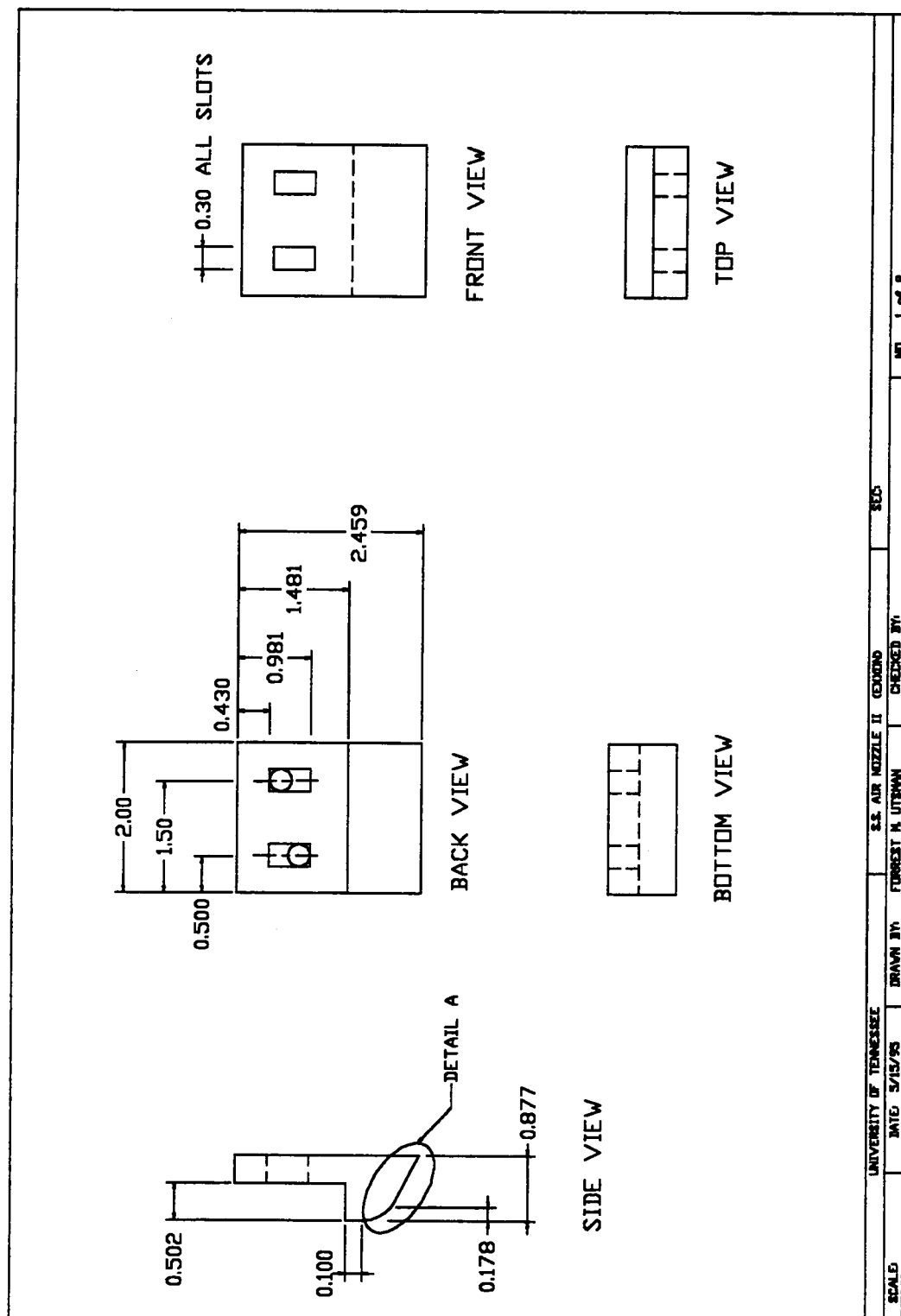


Figure A3: Drawing of upstream c-d nozzle.

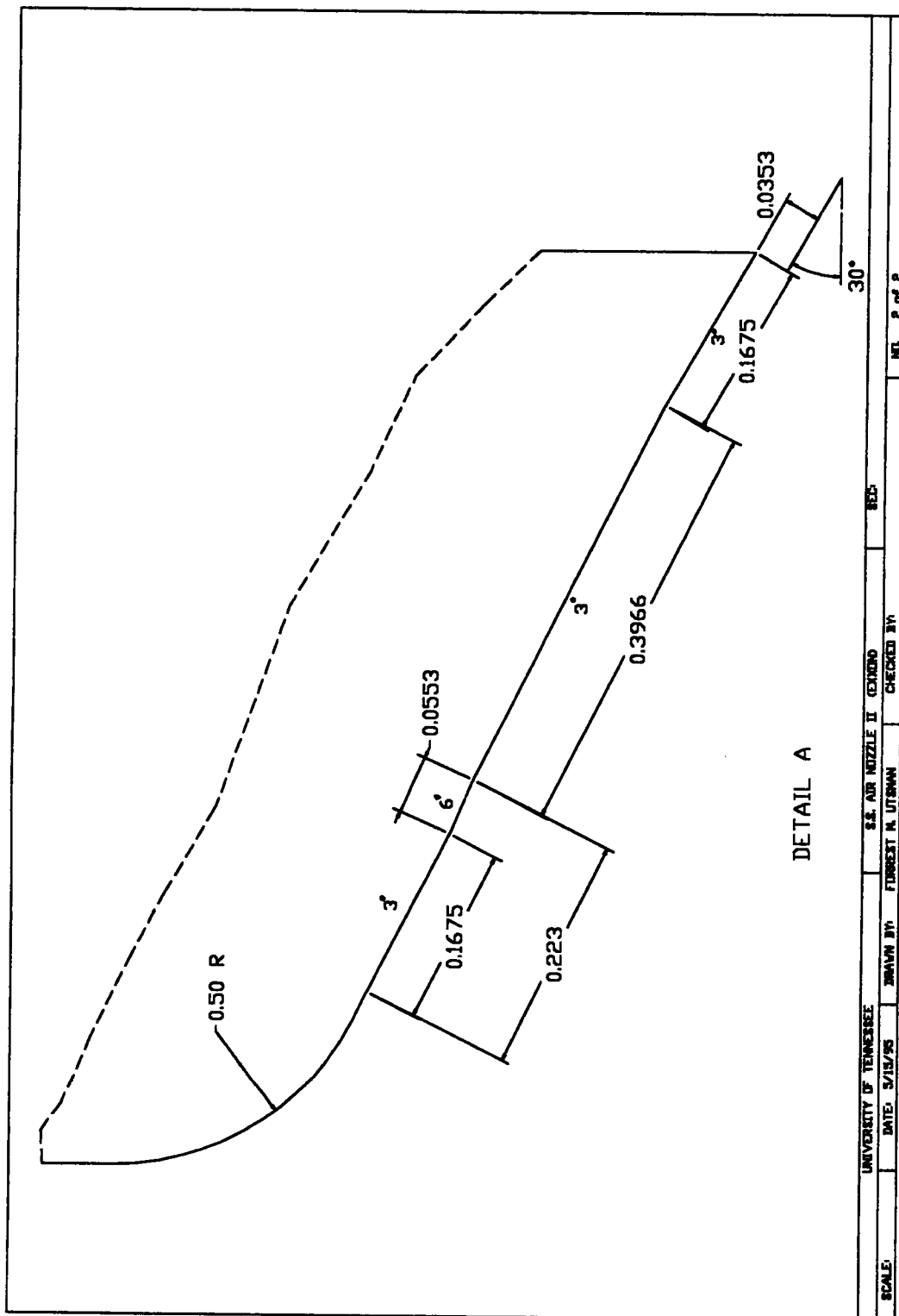


Figure A4: Drawing of upstream c-d nozzle divergent section wall contour.

VITA

Forrest McKae Utsman was born in Johnson City, Tennessee on July 31, 1970. He attended elementary school in Washington County, Tennessee and graduated from Daniel Boone High School with honors in June 1988. In August of the same year, he entered the University of Tennessee, Knoxville, Aerospace Engineering program. In June 1989, he earned his NAUI Advanced and PADI open water scuba certifications. In September 1990, he obtained an engineering co-op position with NASA George C. Marshall Space Flight Center Propulsion Division, in Huntsville, Alabama. While there, he worked on projects relating to gimbling of the Space Shuttle Main Engines and Solid Rocket Boosters. Being a certified scuba diver, he also became a support/video diver in the Astronaut Neutral Buoyancy Simulator Tank. As a support diver, he worked closely with astronauts to help set up simulations for missions such as the popular Hubble Space Telescope Repair Mission. Due to the popularity and importance of this mission, he was featured on local radio and tv newscasts, as well as in local newspapers and magazines. In August 1993, he received a Bachelor of Science degree in Aerospace Engineering from the University of Tennessee, Knoxville. In September 1993, he entered post graduate studies at the University of Tennessee, Knoxville to obtain a Master of Science degree in Mechanical Engineering.

Mr. Utsman is a member of Sigma Gamma Tau, American Institute of Aeronautics and Astronautics, Society of Automotive Engineering International, American Society of Mechanical Engineers, and the National Society of Professional Engineers.