To the Graduate Council.

I am submitting herewith a thesis written by John Thomas Bogard entitled "An Experimental Investigation of Parameters That Influence the Fiber Melt Blowing Process " I have examined the final copy of this dissertation 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 Milligan, Major Professor

We have read this thesis and
recommend its acceptance

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An Experimental Investigation of Parameters That Influence the Fiber Melt Blowing Process

A Thesis
Presented for the
Master of Science Degree
The University of Tennessee, Knoxville

John Thomas Bogard
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ABSTRACT

This study provides a close look at the fiber melt blowing process and what causes the defects (called shot) found in the fabric. There is not much that is known about shot and the experiments presented here provide further insight into what it is and how it is produced. The experimental process in this study of the creation of non-woven material includes testing various polymers, changing the processing conditions, and modifying the geometry of the die. After every experiment, the material was collected and analyzed in order to find the average fiber diameter and the number of shot in each sample. This information provides an objective means of comparing the different experimental parameters such as air and polymer temperature or die air pressure Various extension plates and two different nosepiece designs were considered. The extension plates were not shown to be effective in decreasing fiber diameters or shot. However, the nosepiece with an angled hole design produced some promising results. There was also an in-depth exploration of the issue of shot production The amount of shot found in the samples was compared with temperatures, pressures, and other operating parameters Shot produced by a single hole die was even considered. For the most part, the results are what one would expect from the process of making non-woven material. Shot increases with temperature and decreases with air pressure (up to a point), but it is also influenced by the die-to-collector distance and

throughput. It was found that shot will increase with decreasing die-to-collector distance. Another finding was that changing the throughput will produce changes in the amount of shot seen in a sample. Single hole shot formation was not documented before and there could be several possible explanations for this phenomenon. One possible explanation is that the fiber breaks apart in the air, preventing it from being drawn out properly This document explores this explanation and provides a study of various ways to reduce the formation of shot in melt blown fabrics

PREFACE

Ever since the conception of melt blown materials, there has been much research done in an attempt to create non-woven materials with fine fibers and high filtration characteristics. This research has led to many improvements that have allowed this type of material to become a viable option for use in many applications. Much of the process is believed to be understood and, to a certain extent, the outcome can be predicted As an example, raising the temperature of the polymer provides smaller average diameters but produces more shot This leads one to the question of 'why continue to investigate the fiber melt blowing process?' There are three areas of concern for any research on this process They are the material, the machine, and the collection of the fibers The answer to the above question comes from understanding these three areas and knowing what kind of research has been done on them in the past

The material would simply be whatever is melted down and extruded through the machine. Material is a major concern for many researchers since new materials or even variations of existing ones can react in unexpected ways when they are heated to the operating temperature and extruded through the nosepiece. An example might be attempting to change an existing polymer by mixing in an ingredient that will help it flow more smoothly when it becomes a liquid. The added substance might not respond as expected under the high temperatures and

pressures in the die. The only way to know for certain is to run several experiments with the new material These experiments would need to be run at different temperatures and pressures to be able to fully understand how the new or modified polymer will work. Any company involved in the creation of these new materials has a vested interest in funding research that will help them discover which ones are worth producing and selling

The machine is a mechanical device used to melt the material and extrude it through tiny orifices to create a line of continuous fibers. The melt blown fiber machine uses high temperatures and turbulent airflow to create the small fibers that make up the final material. The basic design has not changed much in recent years since new designs can be expensive to implement and might not provide any significant advantages. The main area of concern for most researchers is how to control the various parameters Air and polymer temperatures can range from 350° F to well over 500° F Air pressure can also be varied from close to 0 psig up to as much as the air supply can provide Throughput is another parameter that can be changed to provide the amount of material needed to achieve the desired results It is easy to understand why modern research is concerned with investigating new materials and determining what conditions produce the best material These parameters are part of this experimental investigation along with some design changes that have shed some light on the process of producing melt blown material

The collection of fibers is considered here as whatever is used to modify and trap the fibers after they exit the die. This includes anything that is used to

manipulate the fibers between the die and the surface of the collector Some research has focused on air, water, or chemical injection into the airstream between the die and the collector to cool the fibers and alter the desired properties of the material. This can reduce shot in the final material and provide material that can be utilized in things such as gas masks. This, along with exhaust vents and other modifications of this type, have been studied, but not much focus has been on the collector itself The method of collecting the fibers to form a continuous sheet of material has not changed much Little is known about how parameters such as die to collector distance or how the surface of the collector can influence the material Further research is needed to understand the correlation between these factors and the final material

The experimental work presented here is an attempt to look at various aspects of the melt blowing process in an attempt to shed some light on the areas not completely understood. Some of the things that will be covered include different die geometries, the correlation between various parameters and shot production, and the issue of single hole shot formation These are just a few of the concepts that are still not completely understood simply because of the nature of the process Without further experimental work in these and other areas, the fiber melt blowing process may never be completely understood and effectively controlled.

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LIST OF ABBREVIATIONS AND NOMENCLATURE

cm	centimeter
de	die orifice diameter
deg	degrees
dg	die gap
ds	die setback
F	Fahrenheit
ghm	polymer throughput in grams per hole per minute
hp	horsepower
MFR	melt-flow rate
mg	milligrams
N'	number of shot
N'/cm^2	shot per unit area
P	die air pressure
psig	gauge pressure
SI	shot intensity in shot per unit mass
Ta	air temperature
Tp	polymer temperature
w	die exit width

CHAPTER I

INTRODUCTION TO THE WORLD OF MELT BLOWN FIBERS

With the improvements made over the years, fiber melt blowing is becoming an economically viable process for producing non-woven fabrics. These non-woven fabrics are being used in any application where fine fibers and excellent filtration is desired. This material is used in clothing such as hospital garments, hair nets, and insulation in winter clothes It may also be used in filters like those found in automotive applications or even in gas masks. Melt blown fiber material can be treated with chemicals to improve its filtration ability One such common treatment is with activated charcoal for gas masks and other types of filters where certain chemicals need to be removed from the fluid passing through the material Even with so many uses for it and the expanding possibilities that the melt blowing industry is addressing, there are still several areas of research that are currently underway to help enhance this material.

The process of melt blowing fibers begins with some type of material (usually a polymer) that is in the form of powder or granules This polymer material is heated beyond its melting point as it goes through an extruder and is forced into a die. The die contains several tiny orifices that reduce the flow of polymer to a small

stream of fibers As the polymer exits the die, it enters a heated jet flow created by two converging airstreams that are contained within the die. This air flow creates a drag on the individual fibers, which stretches them out and blows them up against some type of collector. The fibers build up on the collector and create a continuous sheet of non-woven material

There are several characteristics of the final material that determine its usefulness for its intended application Fiber diameter, number of shot, web thickness, and web strength are some of the characteristics that can be measured through objective means and the results used for analysis of the quality of the web Other characteristics can be measured during tests performed on the web, which can include the "Arizona" dust test or a hydro head test These are for the determination of the material's suitability for filtration applications The look and roughness (or feel) of the web are completely subjective, but are very important when considering the material's application in a product such as protective clothing Those qualities of the web that are subjective in nature are sometimes the result of other characteristics that can be measured. For example, a web that has a "rough" feel will have larger fibers with more shot contained in it than one that feels "soft" to the touch The experimental work detailed here will only cover those characteristics that can be measured in an objective manner

Historically, most of the research on the fiber melt blowing process was concentrated on fiber diameter and the number of shot found in the web. Wente [1] was one the earliest investigators in the fiber melt blowing process; and while attempting to produce ultra-fine fibers, discovered what is called shot. Fiber

diameters and shot formation have been the focus of research ever since The phenomenon of shot is considered to be imperfections found in the web and is often described as a globule of melted polymer, larger in diameter than the surrounding fiber, that adheres to the web By controlling the various parameters of the machine, collector, or the polymer itself, fiber diameters and the amount of shot can be controlled for the most part, to produce the type of material desired. For a more detailed look at the history of the process, see Malkan's [2] dissertation Today, researchers continue their study of the melt blowing process in order to reduce both fiber diameters and the amount of shot produced

The EXXON Corporation has taken an active interest in commercializing the fiber melt blowing process and has funded much of the research in this area at the University of Tennessee in Knoxville The main outlet of the non-woven research is found at the Textiles And Non-wovens DEvelopment Center (TANDEC). This has been combined with work from the department of Mechanical and Aerospace Engineering and Engineering Science which is located in Dougherty Hall. The main concentration of this research has been to provide support for the industry and to improve upon the melt blowing process by studying and controlling the various parameters involved Several improvements including new polymers, die designs, understanding of the process, and control of the process have come from this research and will continue to be the main focus of the experimental work conducted by researchers working under the direction of the EXXON Corporation.

Most of the investigators have endeavored to study what influences fiber diameters and how they can be reduced. Straeffer and Goswami [3] found that

increasing the air velocity will produce smaller fiber diameters. Utsman [4] also explored this effect as he experimented with converging-diverging nozzle designs in an attempt to produce higher air velocities. Malkan [2], Haynes [5], Spencer [6] and many others have explored several other operating parameters and their effects on fiber diameter These parameters include air and polymer temperature, throughput, and polymer melt flow rate (MFR). Kayser and Shambaugh [7] attempted to provide an empirical model that would predict the average fiber diameters Haynes [5] also created an empirical model and then Spencer [6] improved upon this model until predictions were within twice the uncertainty of the measurements of the fiber diameters. Needless to say, most of the experimental work is concentrated in this area and is still not completely understood

The amount of shot found in the web, however, is increasingly becoming an area of interest to researchers today. The question of what shot is and how it is produced is something that is not completely agreed upon by every one in the industry During their experimental work in 1973, Buntin and Lohkamp [8] discovered that the fibers would break at high air velocities They believed that the fibers would break before reaching the collector and then snap back, causing the fiber to create a large globule of polymer. Shambaugh [9] tried to expand upon this idea and described, in some detail, the conditions in which shot is produced. Milligan and Haynes [10], however, found while looking at a single hole die with high speed photography that the fibers remain continuous until reaching the collector Utsman [4] continued to experiment with the processing parameters to discover how they relate to the amount of shot produced

The research presented here is mainly focused upon shot and will try to answer the questions of what it is and how it is produced. Milligan and Bogard [11] presented a broad model to incorporate all of the conditions that can create shot. This model will be looked at in some detail and should provide some help in future studies of this phenomena.

OBJECTIVES

To experimentally investigate the effects of the following parameters on the average diameter and number of shot in melt blown webs:

- four new extension plates were investigated to determine their effect on air flow and the quality of the final web material
- two new nosepieces were also investigated to establish their effects on fiber production and to determine if the process can be improved by controlling resin flowing through the die itself.
- air and polymer temperature, die pressure, throughput, and polymer MFR are the processing parameters that were studied to determine how they relate to shot formation.
- die-to-collector distance was also studied more closely than before to determine how it affects fiber diameter and shot production.
- the collector surface was changed to examine the possibility of reducing the amount of shot found in the web.
- another study of the single hole die provides a better understanding of shot

production by changing the various operating parameters and determining what produces shot

CHAPTER II

EXPERIMENTAL SETUP AND PROCEDURES

Chapter II will take a brief look at the experimental machine used for this study of the melt blowing process and the basic operating procedures used in collecting and analyzing the samples The chapter itself is divided into 3 sections that include the melt blowing facility, data analysis, and WebPro. The first section will cover the experimental apparatus with its supporting air and power supplies along with the collector used to gather the samples. Also included in section one is a brief look at the simple procedures used during every experiment. Next will be the section on how the analysis of the collected samples was accomplished. The final section of Chapter II covers a program called WebPro which is used to analyze non-woven materials This facility and all procedures have been established and used by Utsman [4], Haynes [5] and Spencer [6] and are described in more detail in their theses or dissertation (in the case of Haynes [5]). It should be noted that the EXXON Corporation supplies all of the polymer material used for these experiments and details of the material are considered proprietary

Melt Blowing Facility

The experimental melt blowing machine is located in Dougherty room M1 at the University of Tennessee in Knoxville The machine can be described as having four main sections These are the air supply, screw extruder, die test section, and the collector Figure 2 1 which is not drawn to scale, shows the basic components of the experimental apparatus.

The extruder is a motor driven screw that supplies the die test section with a constant flow of molten polymer resin Figure 2 2 is a simplified sketch of this portion of the machine with its control panel The extruder itself is a Killion unit with a variable speed three horsepower motor turning a single screw with a 30 to 1 speed reducer. Polymer is placed into a hopper that feeds the extruder which forces the material toward the die The extruder has five zone heaters that melt the polymer as it moves toward the die These heaters are set to heat the resin from room temperature to the final temperature of the die The motor can also be adjusted to provide any throughput required for the experiment and the melt pressure is monitored to ensure that the flow of polymer remains constant This process is regulated through the control panel and can be adjusted to provide any polymer temperature or pressure necessary for the experiment Throughput is defined as the amount of polymer in grams that comes out of the die from one hole every minute (ghm) It is measured by simply placing a flat screen in front of the die for one minute, weighing the amount collected on the plate and then dividing the

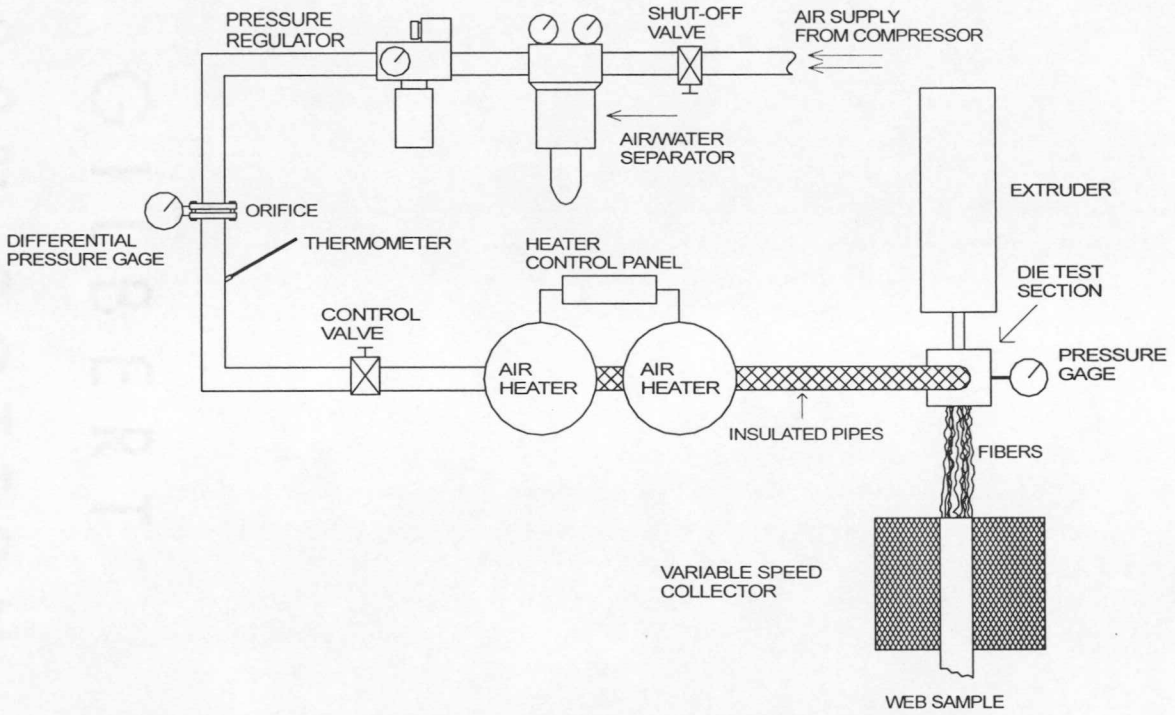


FIGURE 2.1 Simplified Drawing of the Melt Blowing Facility

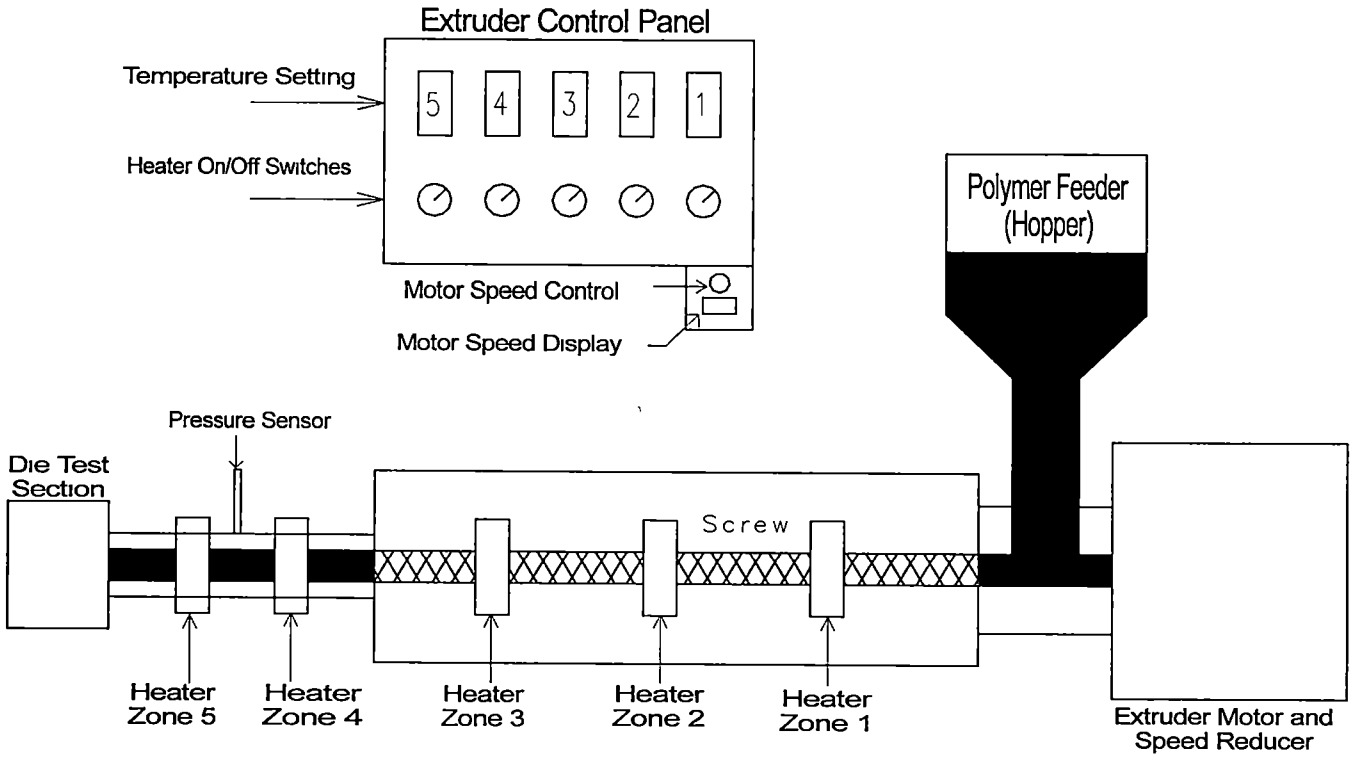


Figure 2.2 Side View of the Extruder and Control Panel

total weight by the number of holes.

The air supply comes from Dougherty Hall's main compressor and goes through a 2" pipe with the necessary valves and instrumentation to measure and control the flow The 2" pipes are more than adequate to provide enough air flow for any pressure required inside the die test section. Two Accutherm air heaters are used in series to raise the temperature of the air to a predetermined setting according to a calibration curve determined by Spencer [6] With the differential pressure, initial preheated air temperature and the pressure and temperature at the die, the air velocity at the opening of the die can be calculated using the equations that were also determined by Spencer [6]

The final portion of the machine that produces the fibers is the die test section This is an insulated steel box that contains K-type thermocouples to measure the air and polymer temperatures along with an air pressure gauge to ensure that the operating conditions remain constant. Figure 2.3 is a cross-sectional view of the die. Molten polymer resin enters the die test section as shown in the figure and travels through a spacer block into the nosepiece Two cartridge heaters keep the resin material at a set temperature as it exits the nosepiece through the small orifices along the edge Heated compressed air enters the die test section from the pipes attached to the top and bottom. The two airstreams then come together at the gap between the faceplates and exit the die along the edge in front of the nosepiece. The result of the two converging airstreams is a turbulent jet flow that creates a viscous drag on the fibers. This drag pulls on the fibers,

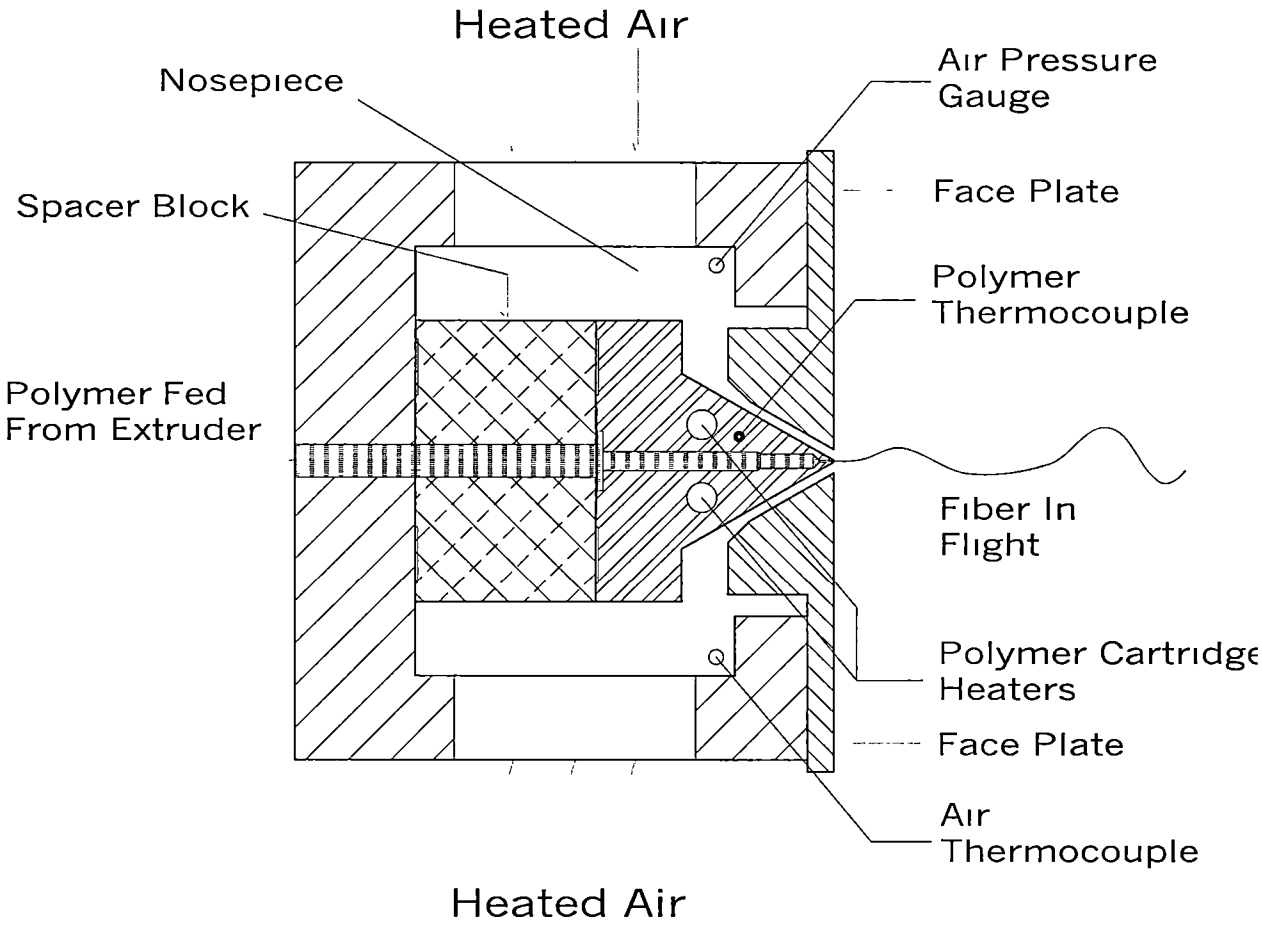


Figure 2.3 Cross-Section of the Die Test Section

causing them to stretch out and become thinner while they are blown up against a collector The nosepiece and faceplates are adjustable and can be replaced to provide different geometries for various test conditions. Figure 2.4 is a closeup, cross-sectional view of the die nosepiece and faceplates that shows the geometry of the three components and their relation to each other. The size of the die orifices (de) is 0 015" in every experiment unless noted otherwise.

The collector is the final part of the apparatus necessary to produce a melt-blowing web As the collector turns, the fibers hit its surface and form a mechanical bond with each other to provide a continuous sheet of material On the other side of the collector, the web material is pulled off and rolled up for later use The collector is an 18.5" diameter drum that has a fine wire mesh screen covering its surface. A combination of a 1/4 hp variable speed motor with a speed reducer designed for a maximum output of 20 rpm is used to turn the drum. By varying the rotational speed of the drum, different web thicknesses can be obtained.

Web Analysis and Data Reduction

For each web sample that is collected, diameter and shot data is necessary to evaluate the performance of the material. Fiber diameters are measured by taking a piece of a sample and visually inspecting it under an Olympus microscope at 400X magnification. This microscope is equipped with a lens that has a superimposed scale on it for measuring the diameter of individual fibers. With each

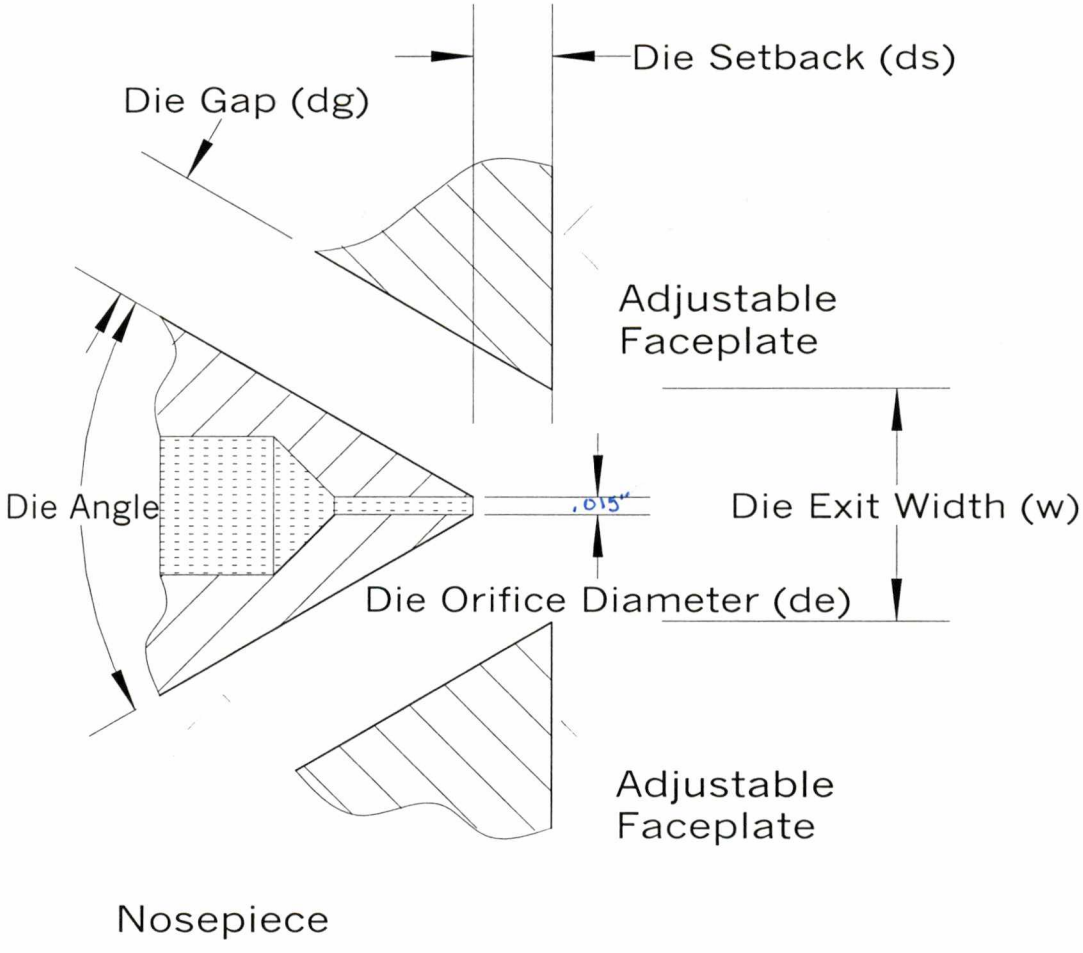


Figure 2.4 Close-up View of the Die Geometry

increment on the scale measuring 2.5 microns, fibers can be measured within ±1.25 microns. At least 30 fibers from each sample are measured for their diameters and those values are placed into a spreadsheet. The spreadsheet program can then be used to determine the mean diameters, standard deviation, coefficient of variance, and maximum and minimum values to allow for comparison of different samples. This process of measuring and collecting the data, along with its validity, has been established by Haynes [5] and Spencer [6].

The amount of shot found in a sample is determined by using two different methods. The first of these is similar to the visual inspection process that Utsman [4] described and used. The second is accomplished by using WebPro which will be explained in the next section. Visually inspecting a sample involves cutting out a 1" square piece of material and examining it with a microscope at 40X magnification. Under the microscope, the entire sample is scanned and all of the visible shot is counted. The method used by Utsman [4] to provide shot intensity was modified to provide a more consistent and objective manner of evaluating what is shot. It has been established in the past by Utsman [4] that any piece of shot found in the web would be counted. This method was done strictly by visual inspection and could produce different results if more than one person analyzed the same sample or if the samples had varying thicknesses. The thickness of the samples is now controlled by regulating the rpm of the collector which accounts for some of the inconsistencies. Also, shot is measured and classified in three categories by using the scaled lens in the Olympus microscope. The categories include a range of measurements for each piece of shot. The ranges are from 50

to 100, 100 to 225, and larger than 225 microns Each range was chosen for a specific reason to aid in the understanding of the amount and type of shot in the sample. The 50 to 100 micron range provides a look at how many pieces are in the material that normally would not have been counted. The second range was found to be the size where most of the shot would be. The largest range is, of course, where all other pieces would fit. When calculating shot intensity, only the number from 100 microns and larger would be counted This number is then divided by the weight of the sample to provide shot intensity as shown in the following equation

$$Shot.Intensity.(SI) = \frac{Number.of.Shot.(N')}{Weight.of.Sample.(mg)}$$

In this manner, different samples that vary in thickness and weight can be compared to each other.

At this point, it would be beneficial to define visible shot in fiber melt blown webs Visible shot is nothing more than shot that can be seen without any magnification Most people can see a thin fiber and even a human hair that is 100 microns or larger when it is placed on a background that contains some contrasting color The size of visible shot is considered to be the approximate diameter of a globule that is 100 microns or larger. This size would be similar to a cross-section of a fiber or hair that can be seen, except shot often has an irregular shape When looking at a web, shot is often hidden from sight because it is the same color as the surrounding web material In a web sample, the size of shot that typically can be seen without any magnification is usually larger than 225 microns which is the

largest range of shot that is counted.

WebPro Analysis

Another method for analyzing a sample is accomplished by using a technique called WebPro This program is a creation of Yan and Bresee [12] and can be used to analyze any nonwoven material. It has the capability of measuring diameters and the amount of shot in the samples faster and more consistently than it can be measured by visual inspection. The technique can also be modified to adjust for varying conditions and types of samples as well WebPro operates on a computer that controls a camera mounted on a moving track It works by taking a series of images of a sample that has been laid out on a table with a lighted background. These images are then processed to find the number of shot or the diameters of several fibers in each image Yan and Bresee [12] explain WebPro in more detail and how it can be used for measuring shot in melt blown webs This process can go through several images in a relatively short period of time and the results for shot analysis are presented in terms of shot per unit area as seen in the following equation

$$Shot/Unit.Area.(N/cm^2) = \frac{Total.Number.of.Shot.Found.(N')}{Total.Area.of.Images.(cm^2)}$$

For counting shot, the program has been evaluated and was determined to be consistent and able to provide acceptable results for analyzing non-woven

samples as shown in the following experiment. An experiment was done with the intention of verifying the results obtained from using WebPro with the machine setup using an air and polymer temperature of 500° F and a die pressure of 5 psig The throughput was also kept at a constant 0 8 ghm with the collector placed at a distance of 16" from the die. The die itself contained the 30 hole, 60° nosepiece and the die setback and gap were both set at 0.079" The experiment was designed to run the machine at constant conditions and then vary the collector speed to produce material at three different web basis weights Basis weight is simply the amount the sample weighs per square yard or meter For this experiment, the three weights are 1.0 Oz/SqYd, 1 4 Oz/SqYd and 2 5 Oz/SqYd For each of these basis weights, one long sample was made and then divided up into five pieces so that they could be analyzed separately. In this manner, five samples were collected, that were essentially part of the same material, in order to verify the consistency of both shot measuring techniques The total number of shot was counted using WebPro and by visual inspection under a microscope and then these numbers were divided by the area of the sample Table 2 1 shows the results of each method of counting shot. By looking at the coefficient of variance, WebPro varies more than the measurements taken by using the microscope method but both are within reasonable limits Also, visual inspection of the sample using a microscope produces much larger values for shot per unit area This is due to the fact that a person can find shot much easier than a computer program because the person can recognizing a globule of polymer whether it is laying on the surface of the web or if it has melted through the web This experiment indicates that as long

Table 2.1 Information From the WebPro Verification Run

	Sample Number	N/cm^2 WebPro	N/cm^2 MICROSCOPE
1.0 Oz/Yd^2	1	0 12	4 7
	2	0 12	4 0
	3	0.19	3 4
	4	0 12	3 6
	5	0 12	4 2
	Mean	0.13	3.97
	Standard Deviation	0 028	0 44
	Coeff of Variance	0 21	0 11
	Confidence Interval	0.13±0.035	3.97±0.55
1.4 Oz/Yd^2	1	0 09	4 8
	2	0 10	4 0
	3	0 04	2.8
	4	0.13	4 3
	5	0 12	3 7
	Mean	0.10	3 94
	Standard Deviation.	0.031	0 68
	Coeff of Variance	0.33	0.17
	Confidence Interval.	0.10±0 038	3.94±0.84
2.5 Oz/Yd^2	1	0 09	1 9
	2	0 05	2 8
	3	0 15	3 0
	4	0 10	3.7
	5	0 08	3 4
	Mean.	0.09	2.95
	Standard Deviation	0.033	0.64
	Coeff of Variance	0.35	0 22
	Confidence Interval	0 09±0 041	2 95±0 79

as thinner samples are analyzed, either method will produce acceptable results and it shows the consistency of WebPro along with some of its limitations. It should be noted that samples measured with one method cannot be directly compared with those measured with the other method

The uncertainty of each method can be considered by first assuming that any errors introduced would follow the probability of a t-distribution curve for a small number of samples This curve and information can be found in most books on statistics, but the information here is provided by Beckwith, Marangoni, and Lienhard [13]. One way to evaluate this type of problem is to use a 95% confidence interval with the number of degrees of freedom being the number of samples minus one. This provides a t-distribution value of 2.776 from Table 3.6 in Beckwith, Marangoni, and Lienhard [13]. The intervals shown in Table 2.1 after each sample indicate that both WebPro and counting shot by a microscope produce acceptable intervals. A conservative interval for these samples, can then be given as +/- 1 N/cm^2 for the microscope method and +/- 0 05 N/cm^2 for those results given by WebPro. Notice that the thicker and heavier samples have a lower mean value but a higher interval than the 1.0 Oz/SqYd samples for both methods, which indicates that the thicker samples are more difficult to analyze and results in a higher variation in measurements.

The drawbacks of WebPro are its expense, complexities, and the need for uniform web thicknesses WebPro requires the difficult process of setting up a table with a lighted background, a camera mounted on a moving track and a computer for controlling it The table must be level and stable, and the camera must have a

high enough resolution with a zoom lens to be able to focus on a relatively small section of the sample A DA converter must be used to move the camera, and the images must be converted from an analog to a digital signal in order for the program to process them. These components along with the time and space needed to set them up are in can be quite expensive The computer program itself is also complex because it is necessary to fine tune it so that only shot is counted and not thin spots in the web or anything else it might be interpreted as a shot. There are many adjustments to make in order to set up the program initially including camera movement, contrast, lighting, size and scale of each image, and sensitivity just to list a few. Because of its complexity, it is necessary for the user to have some experience in order for WebPro to be effective. The other drawback is the basis weight and the important role it plays on what is being measured in the samples. For measuring diameters, a sample with a small basis weight is needed so that the program can find the edges of the fibers. On the other hand, samples with a higher basis weight are necessary for WebPro to distinguish between the web and a solid globule of polymer when counting shot The different sample thicknesses required to measure average diameters and shot make it inconvenient to do both on a single sample so that only shot was analyzed for the experiments here.

CHAPTER III

ALTERNATE DIE DESIGNS

Most experimental work is on the control of various parameters such as polymer throughput, air temperature, or polymer MFR; however, this chapter will look at some unique die designs that controls either air or polymer flow Airflow is considered in the first part of the chapter with a simple way to constrict the flow just as it exits the die test section. The second section considers a modified nosepiece design that can be easily made. The last section also addresses a modified nosepiece that has the possibility of producing a higher quality web. These die designs were an attempt to improve the desirable characteristics of the final web such as smaller fiber diameters and reduced shot Each die modification was tested and compared to a "standard" setup which will be described in more detail. There are two things to keep in mind for each new design and those are what it will do to the final web and how easily it can be implemented on new or existing machines used in the melt blown fiber industry

Extension Plate Study

The idea behind an extension plate is simply to add a metal plate to the face of the die test section as shown in Figure 3.1a The main function of the two plates is to constrict the air flow as it expands from the narrow slit between the faceplates. This constraint on the flow of air limits the flapping motion of the fiber until it is past the extension plates. Another possible benefit of the constriction is that it creates a crude converging-diverging nozzle which can accelerate the air velocity to supersonic speeds This higher air velocity has the potential of creating smaller fiber diameters or even reducing the amount of shot made in the web. Utsman [4] considered different converging-diverging nozzle designs including a set of 0.5" thick extension plates

The air flowing out of the die is essentially the classical 2-dimensional turbulent jet flow phenomenon. It can be treated as a 2-dimensional flow since the die is 4" wide compared to the height of the opening which is less than 0 1" Utsman [4] and Haynes [5] also noted this resemblance to a classical free jet flowfield. The free jet flowfield has been studied in depth by many people in the past and is covered in most fluid text books including White [14] Utsman [4] determined the relationship between the centerline velocities and the distance from the die using the machine in Dougherty room M1. These are close to the values given in the theoretical equations for a free jet flowfield. Figure 3.2 is a simplified sketch of this flow with the dashed lines indicating the boundaries. Figure 3 3

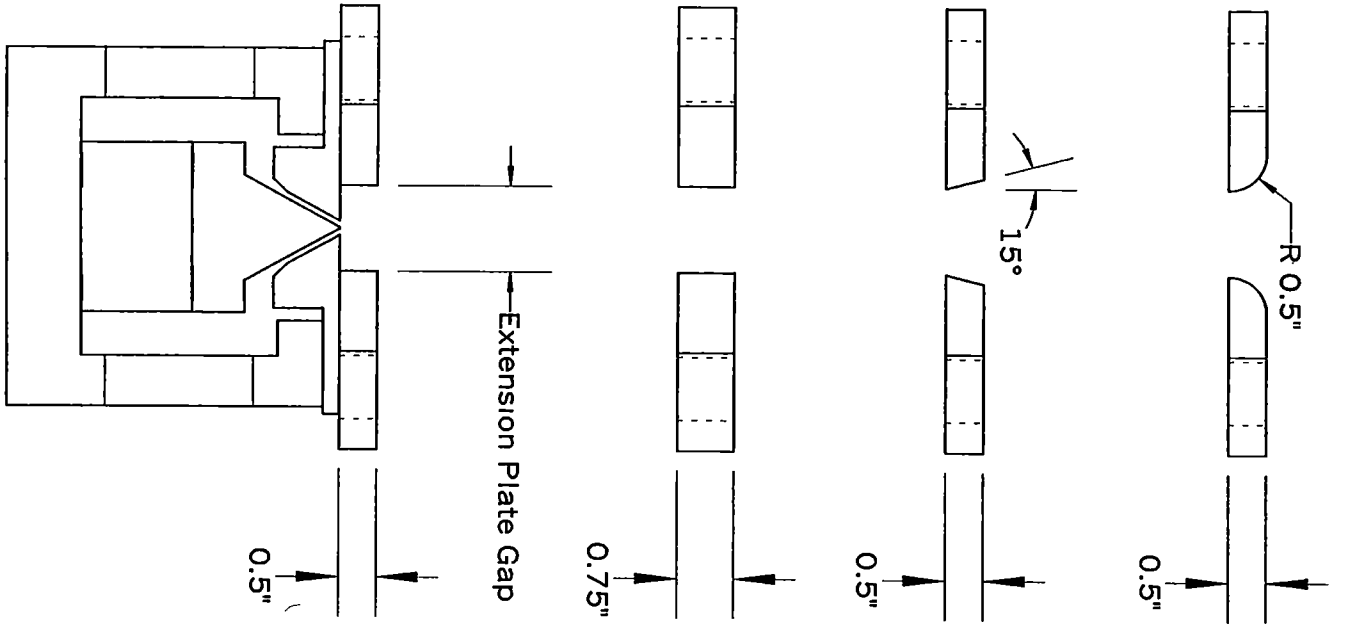


Figure 3.1a Figure 3.1b Figure 3.1c Figure 3.1d

Figure 3.1 Side View of Die Test Section With Extension Plates

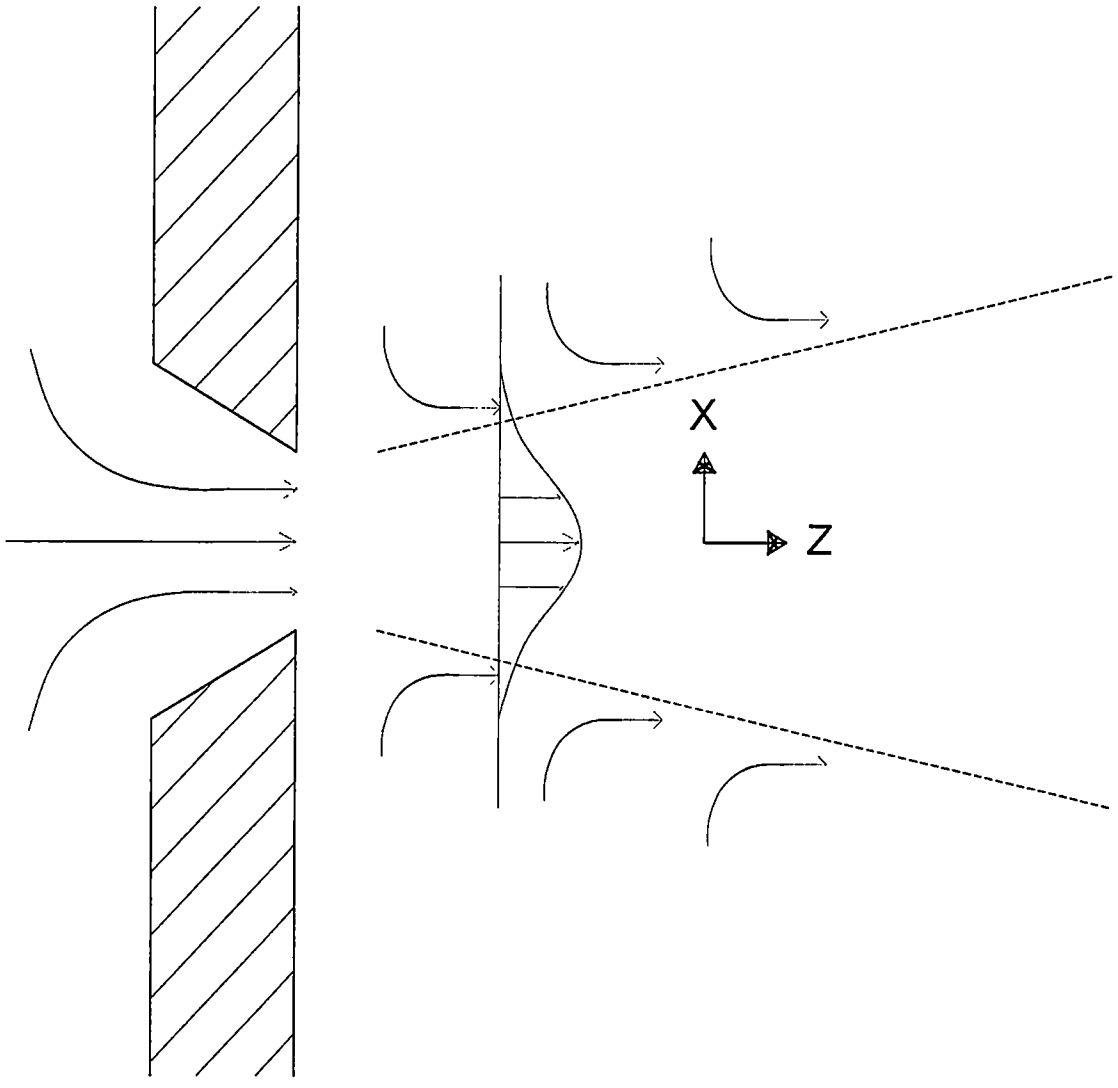


Figure 3.2 Sketch of Classic Free Jet Flowfield

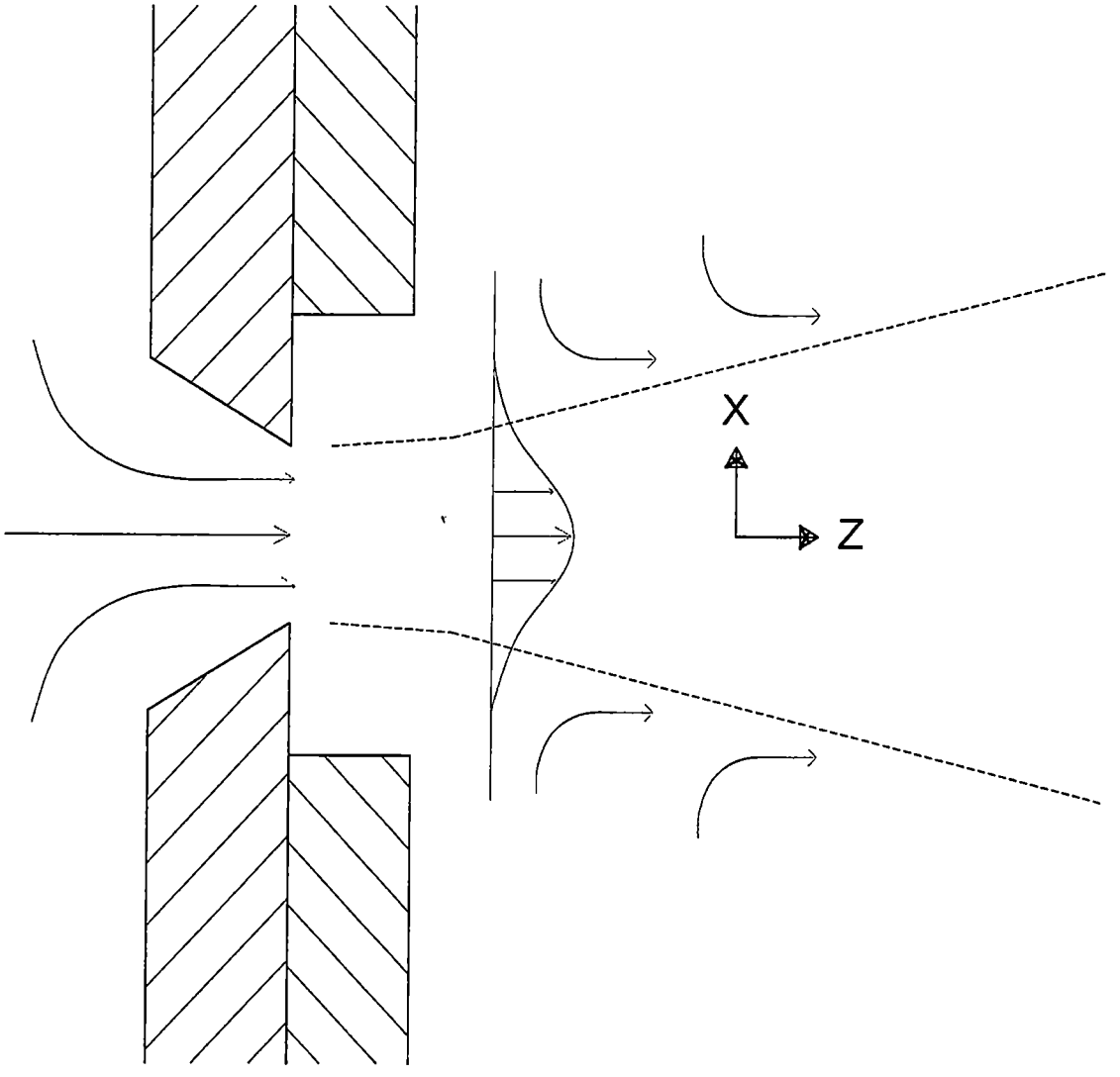


Figure 3.3 Sketch of Modified Free Jet Flowfield

shows two extension plates added and their possible influence on the flow. The plates create a step that delays the effect of the entrained airflow, which adds to the mass of the air moving along the centerline of the die. This step also slows the expansion of air until the airstream gets past them. Such a change in the flow of air should have some effect on the fibers as they are drawn out from the 0.015" holes in the nosepiece to the resulting fiber sizes found in the web that are measured in microns.

There are four different extension plates considered here with the design of each shown in Figures 3.1a through 3.1d. The first is the same 0.5" thick set of plates that Utsman [4] experimented with as seen in Figure 3 1a. The second is the 0 75" thick extension plates. Then there is a set of plates with a 0.5" thickness and an edge angled 15° away from the centerline of the die. The last set of plates are also 0.5" thick; however, the edges have a 0.5" radius. All of the extension plates were placed on the die in the same way with the gap between them set at a distance depending upon the size and shape of the plates. This extension plate gap is centered about the centerline of the die itself

A total of 8 different cases were considered for these extension plates. The first of which is the standard die setup with no extension plates and it will be used for comparison with all of the other cases. This setup is a 30 hole, 60° nosepiece with the die setback and gap at 0.079". In each case the air and die temperature were set at 500° F, the die to collector distance was kept at 16", and the pressure was varied between 2 and 12 psig. The second and third cases were with the 0.5" extension plates placed on the original setup and spaced at 0 5" and 0 75" apart

from each other respectively. Since the 0.5" case is the same one that Utsman [4] did, the plates were spread to a 0 75" spacing to see if it would make any difference to the final web The fourth case involved the 0.75" extension plates spaced at 0 75" apart This distance was found to be the closest that they could be placed together without the fibers touching the edge and causing molten pools of polymer forming along the plates. The next two cases involved the 0 5" extension plates with the 15° angled edge. Two distances were considered with the first at 0 5" gap between the two plates at the nearest point between them as shown in Figure 3 1c. The second distance was set at a gap of 0.33" which is the closest distance that they could be placed together without the fibers touching the edge of the plates. The final two cases involved the 0.5" plates with the 0.5" radiused edge. For these plates, the gap was set at 0.5" and then at 0 25". Again, 0.25" was the closest distance that they could be placed together without the fibers touching them

By looking at the first two cases, the 0.5" extension plates are given another comparison to the original setup along with the experiments that Utsman[4] considered. With the higher air and die temperature than what he looked at, the fiber diameters should be smaller and the amount of shot produced should go up In Figure 3 4, the diameters of the two cases are compared with the results not showing anything conclusive about case 2. The difference between the points of each of the two cases are within the margin of error for the measurement scheme used to analyze the samples. This is the same as what Utsman [4] found by looking at these two setups Figure 3.5 shows that the amount of shot produced is also

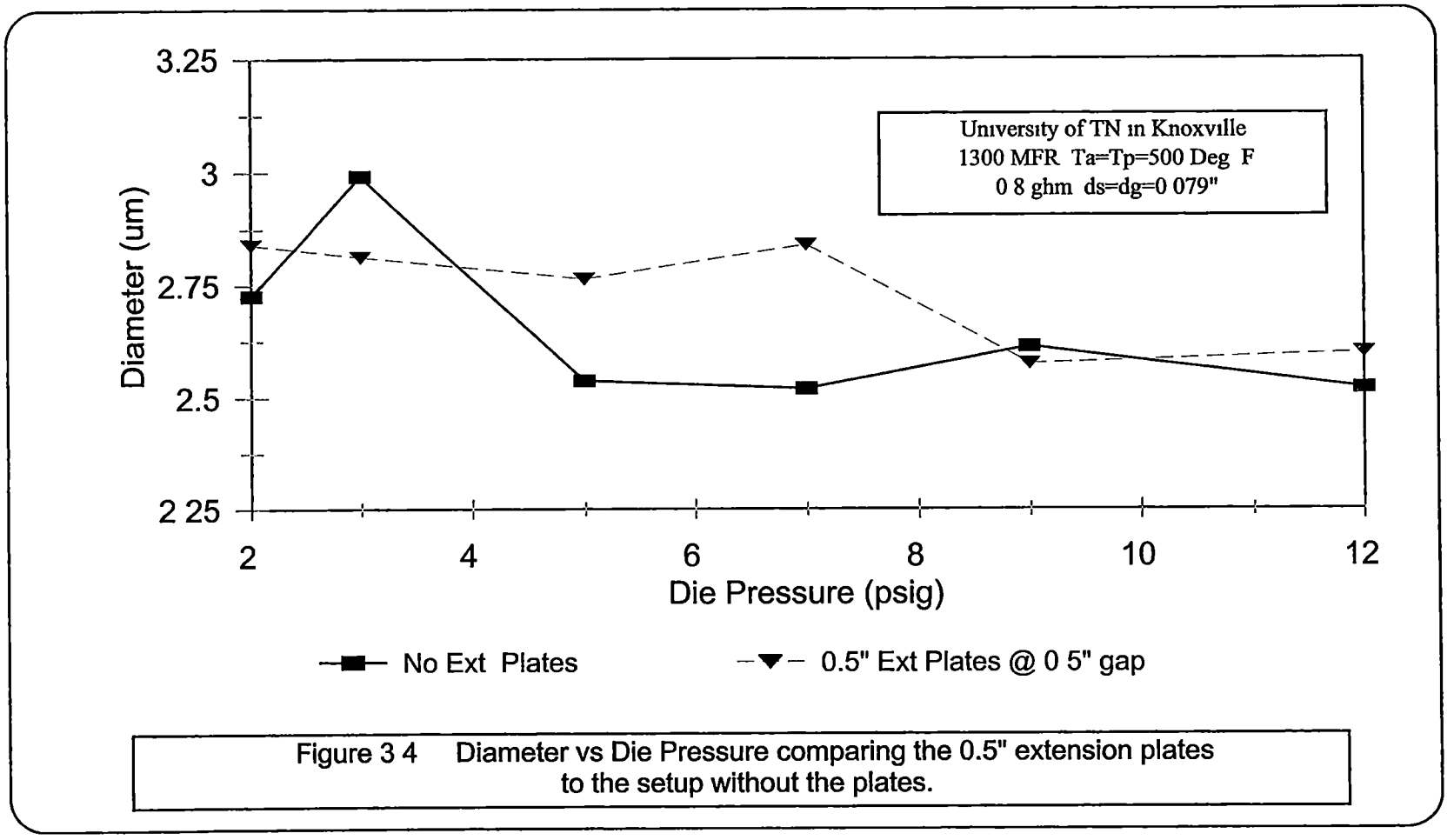


Figure 3 4 Diameter vs Die Pressure comparing the 0.5" extension plates to the setup without the plates.

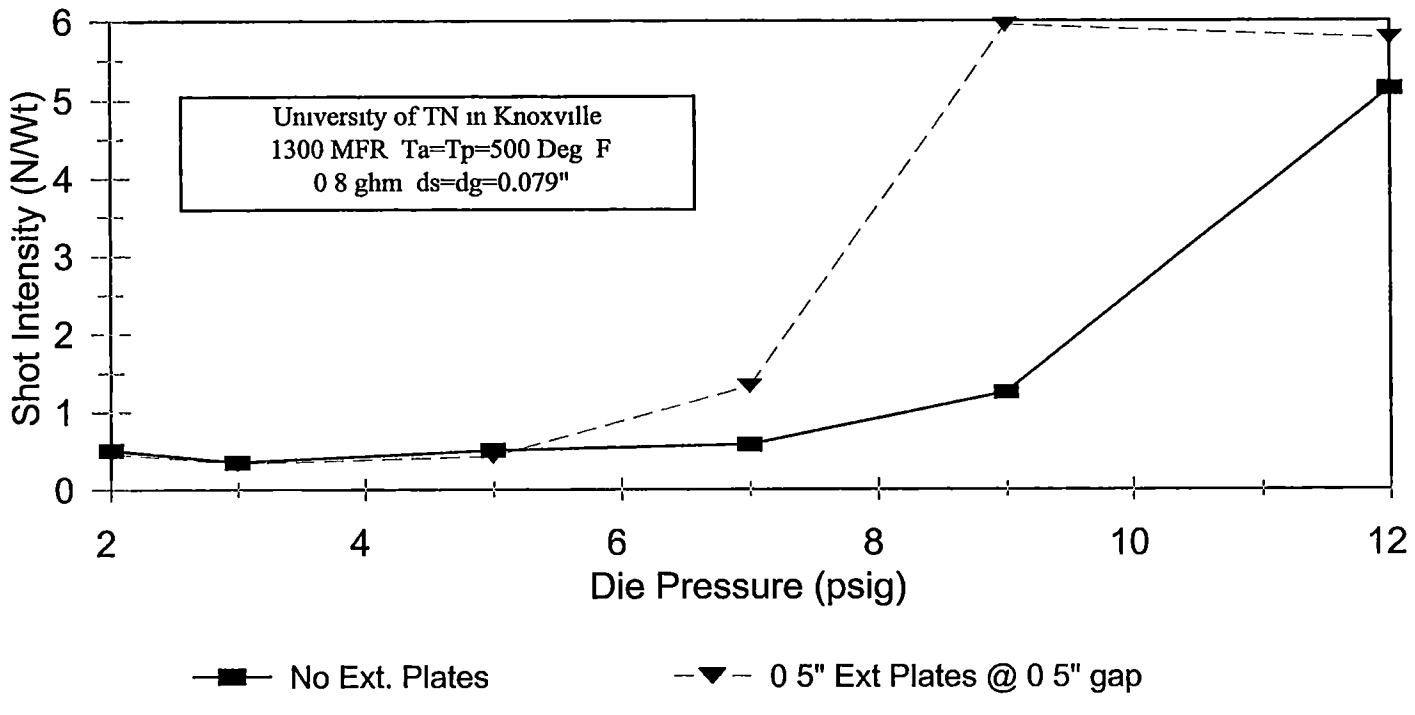


Figure 3.5 Shot Intensity vs Die Pressure comparing the 0.5" extension plates to the setup without the plates.

very close until the die pressure reaches 7 psig and then the 0.5" extension plates cause this amount to grow more rapidly than the standard setup The higher pressures are not usually seen in any industrial application but it does provide a look at what happens at the extremes Figure 3.6 shows what happens to the shot intensity at the lower pressures Again, the amount of shot produced is very close from the 0 5" extension plate case to the original setup at the lower pressures. From this data, the 0.5" extension plates do not show any noticeable improvement over the standard setup when it is set at a 0.5" gap.

The next setup is with the same extension plates set at a 0 75" gap to see if the change will make a difference to the final web. With the plates spread farther apart, the fibers do not come close to touching the edge of the plates. The data shown in Figure 3.7 indicates that the plates have virtually no effect on the average diameters. Figure 3.8 also shows what happens with the shot intensity data and again, there is no effect on the final web. This could indicate that the extension plates are moved out of the airflow and therefore would not affect the outcome of the final web.

With the 0.75" extension plates and the gap set at 0.75", the data demonstrates that these extension plates can have an impact on the final web material. The diameter information in Figure 3.9 shows that the thick plates cause the fibers to be much thicker at lower pressures when compared to the standard setup. Also the amount of shot found in the sample is much higher throughout the entire range of pressures as shown in Figure 3.10 These thicker plates produce

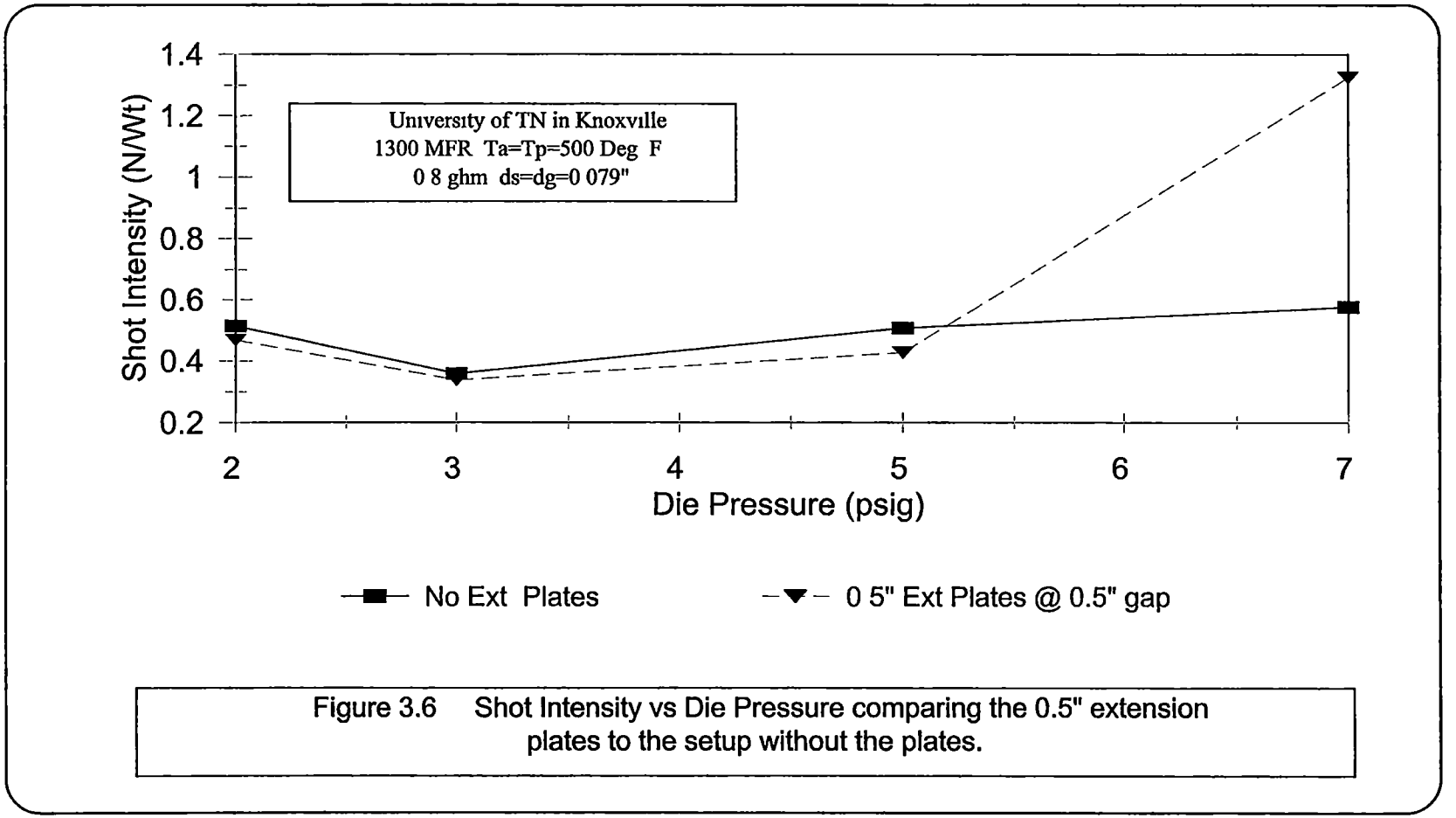


Figure 3.6 Shot Intensity vs Die Pressure comparing the 0.5" extension plates to the setup without the plates.

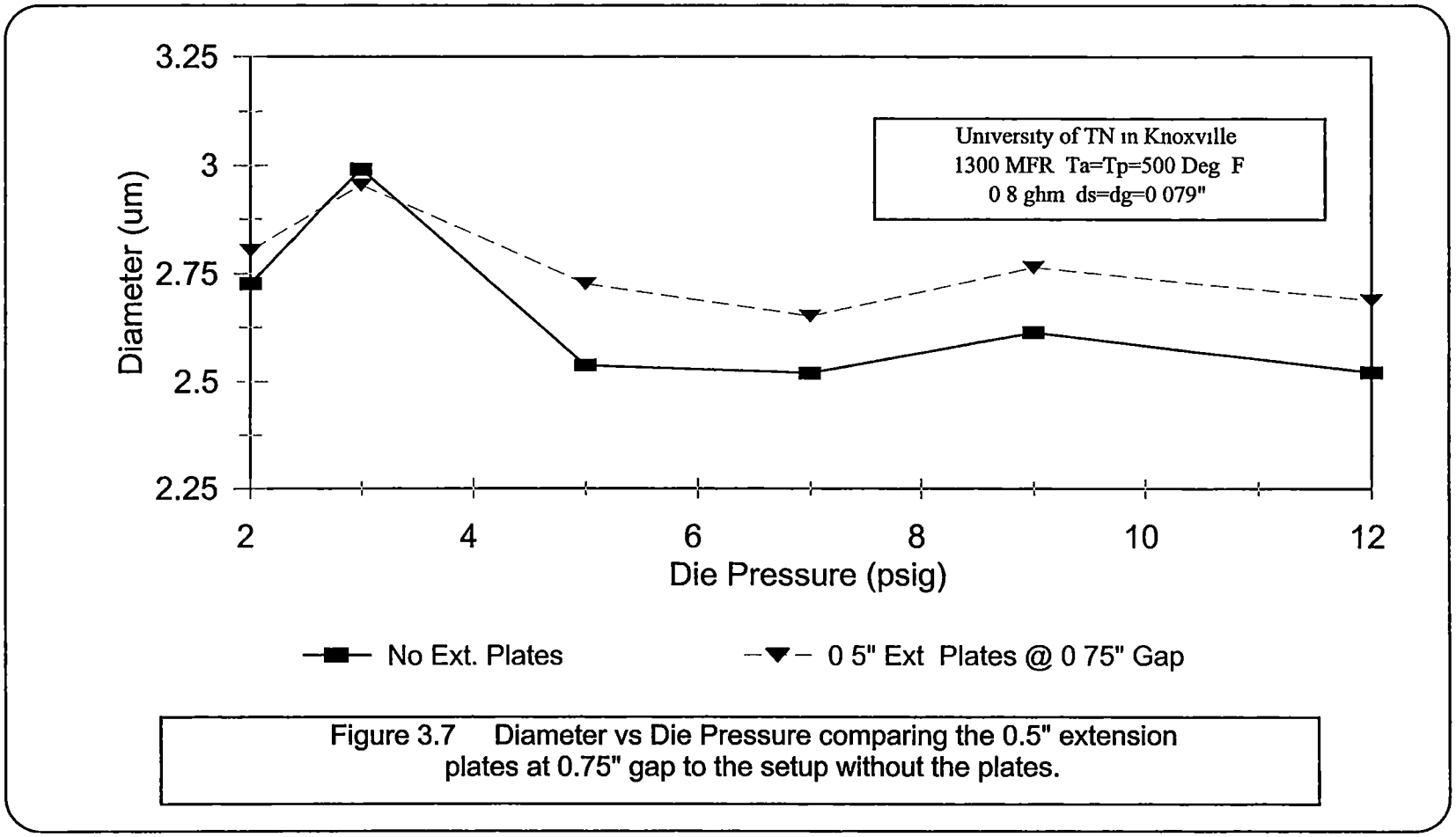


Figure 3.7 Diameter vs Die Pressure comparing the 0.5" extension plates at 0.75" gap to the setup without the plates.

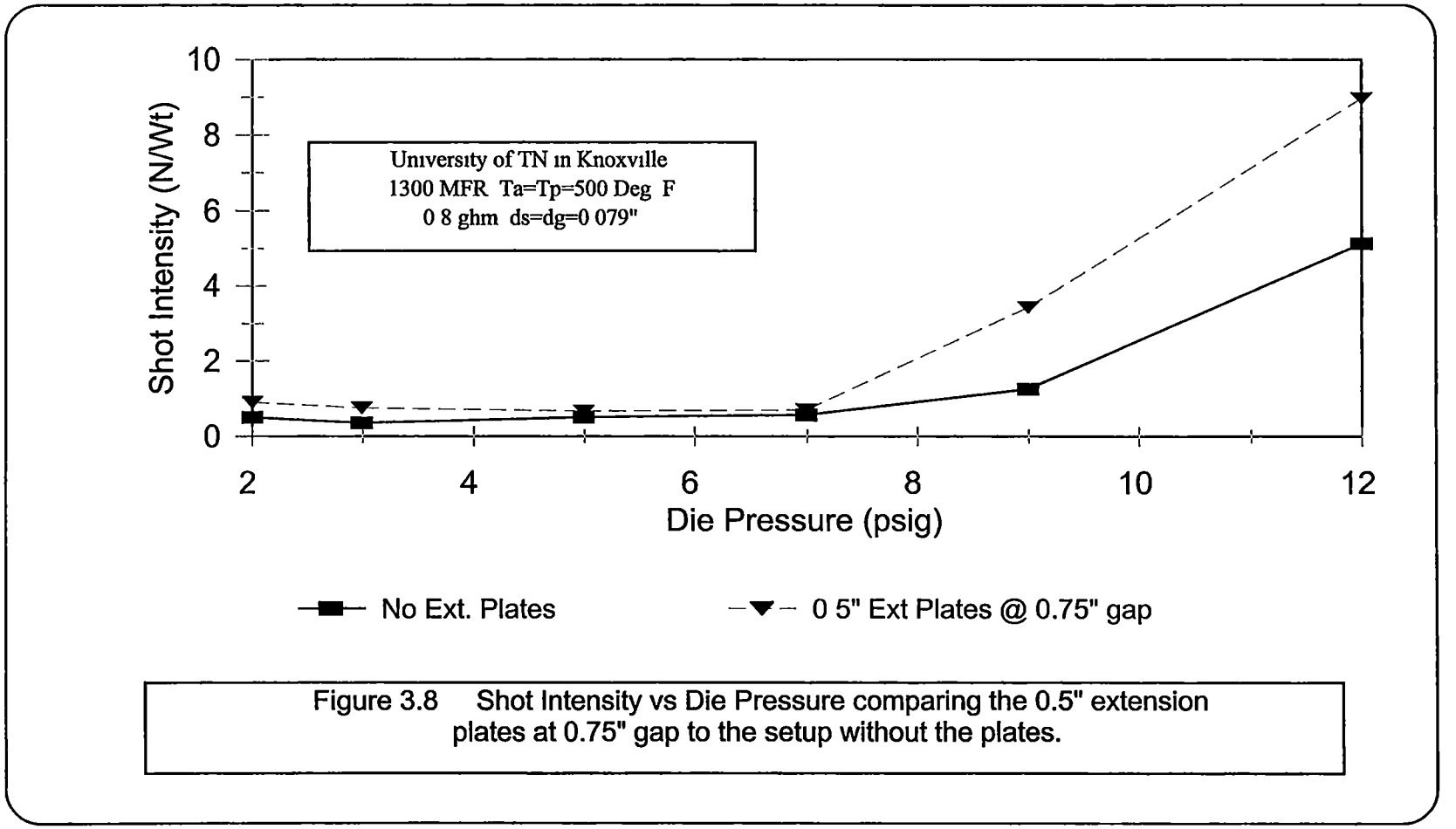


Figure 3.8 Shot Intensity vs Die Pressure comparing the 0.5" extension plates at 0.75" gap to the setup without the plates.

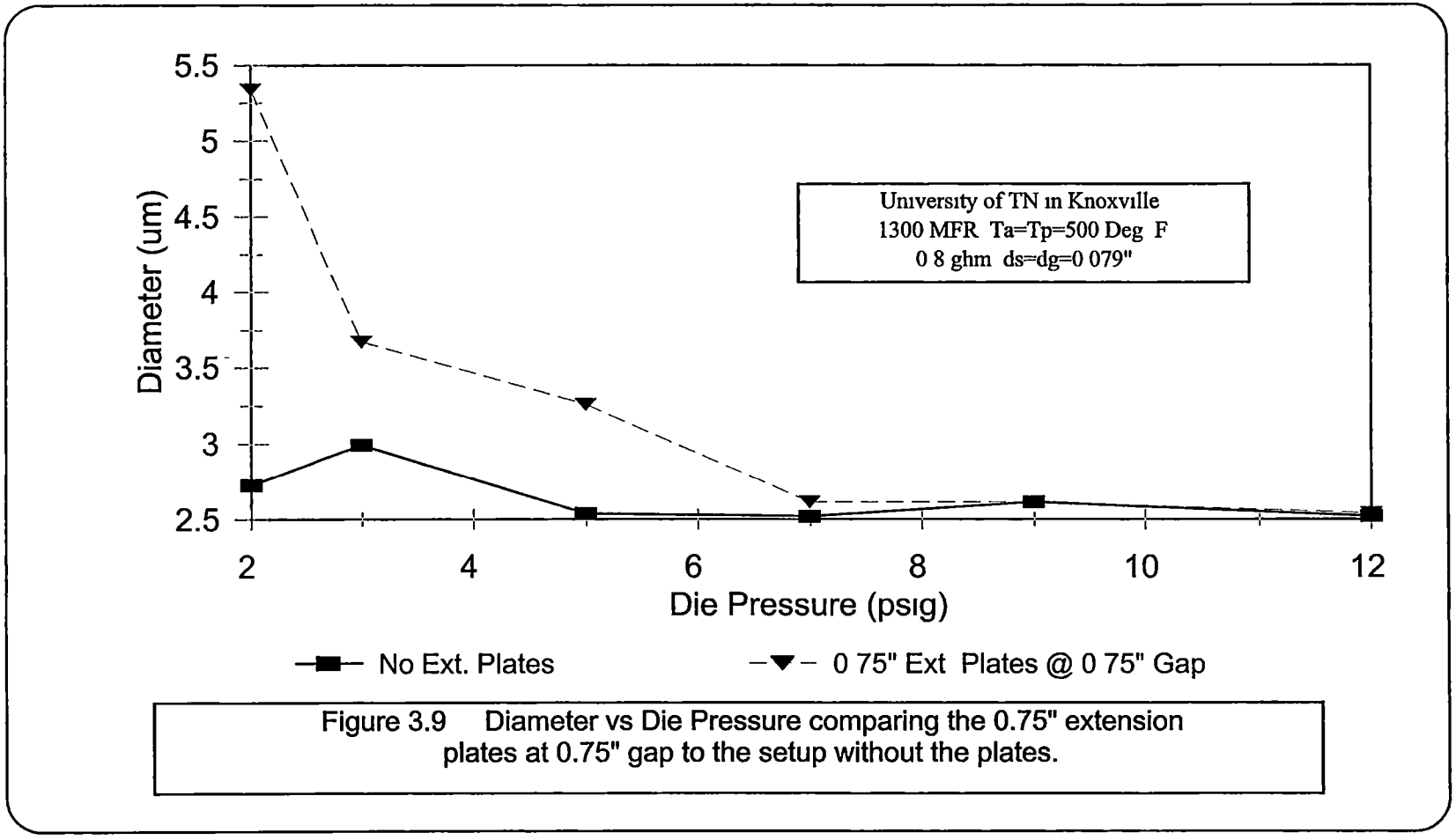


Figure 3.9 Diameter vs Die Pressure comparing the 0.75" extension plates at 0.75" gap to the setup without the plates.

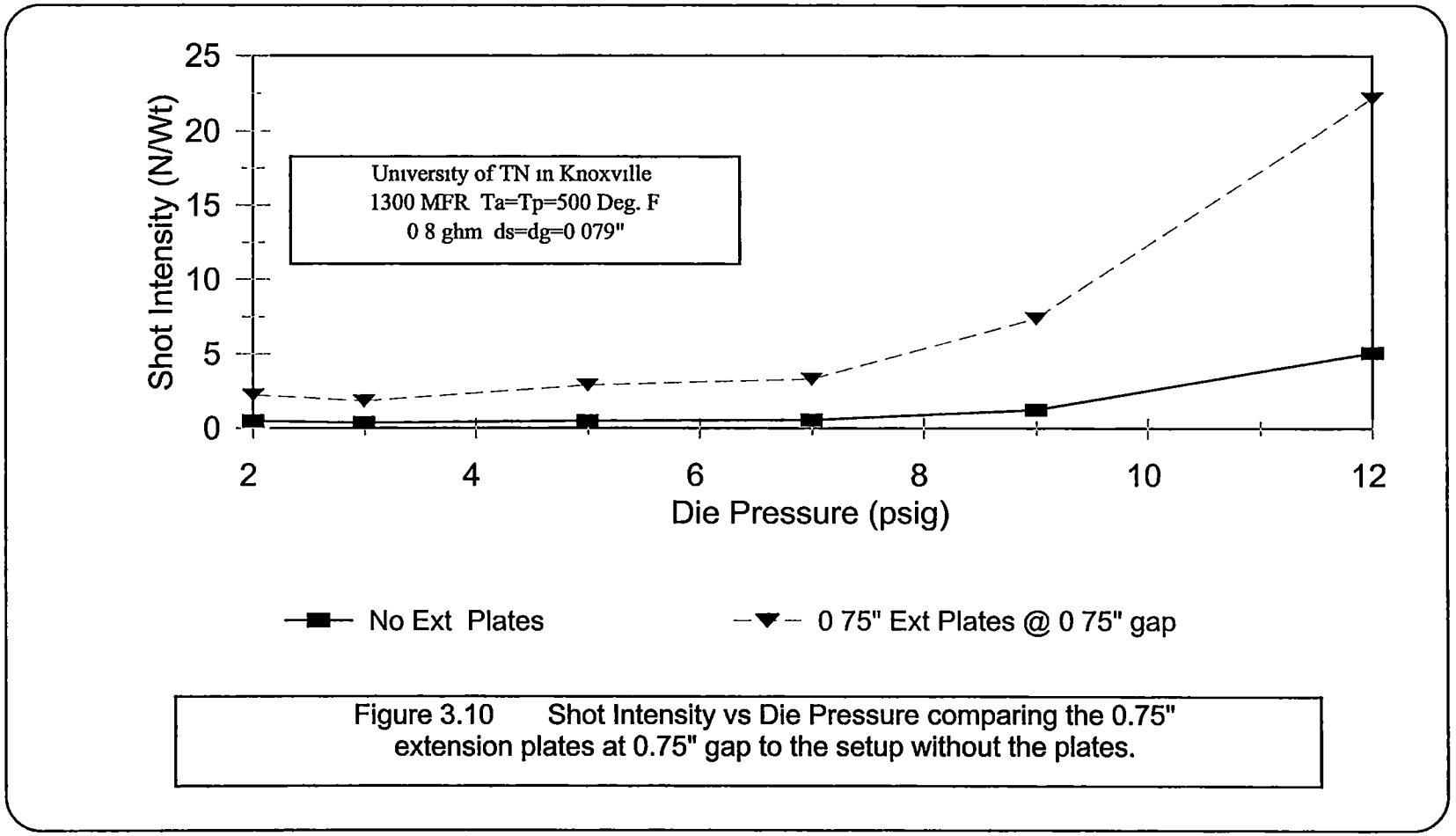


Figure 3.10 Shot Intensity vs Die Pressure comparing the 0.75" extension plates at 0.75" gap to the setup without the plates.

web material that has worse characteristics than that produced by the standard setup, which indicates that there is a change in the airflow as it exits the die. This change is apparently due to the reduction of the entrained airflow which adds to the overall mass of the air moving along the centerline of the die The reduction of the mass of airflow could reduce the flapping motion of the fibers that results in them being stretched out

The next set of extension plates studied is the 0.5" thick plates with a 15° angled edge. With a 0.5" gap, these plates provided average diameters that are very close to the standard setup as shown in Figure 3.11. This could be due in part to the fact that the angle of the edge keeps the plates from affecting the airflow However, the shot intensity shown in Figure 3.12 indicates that something changes that results in almost double the amount of shot produced over the standard setup. In this case, the amount of shot produced is doubled at almost every point. When the plates are moved closer together to a 0.33" gap, the average diameter increases at every point. Figure 3.13 demonstrates this increase at the closer gap This change could be due to the same factors that caused the change in the 0 75" extension plate case at a 0.75" gap For the 0 33" gap, the shot intensity was not counted since the diameters show an increase throughout the entire range of pressures and this setup was not deemed practical.

The final two cases involve the 0.5" extension plates with the 0.5" radiused edge. First, the plates were set at a 0.5" gap and compared with the standard setup Figures 3.14 and 3 15 contain the average diameter and shot information.

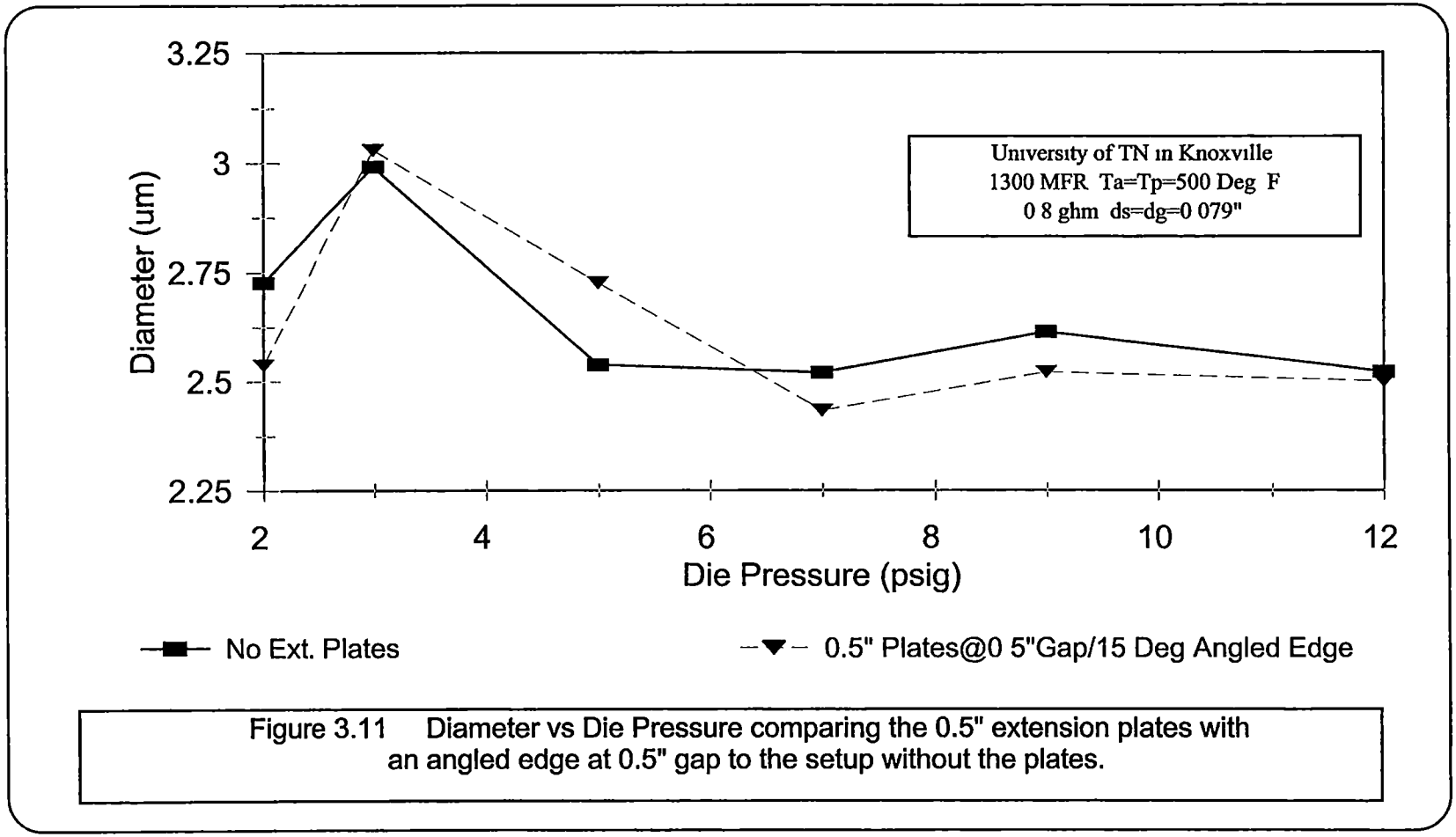


Figure 3.11 Diameter vs Die Pressure comparing the 0.5" extension plates with an angled edge at 0.5" gap to the setup without the plates.

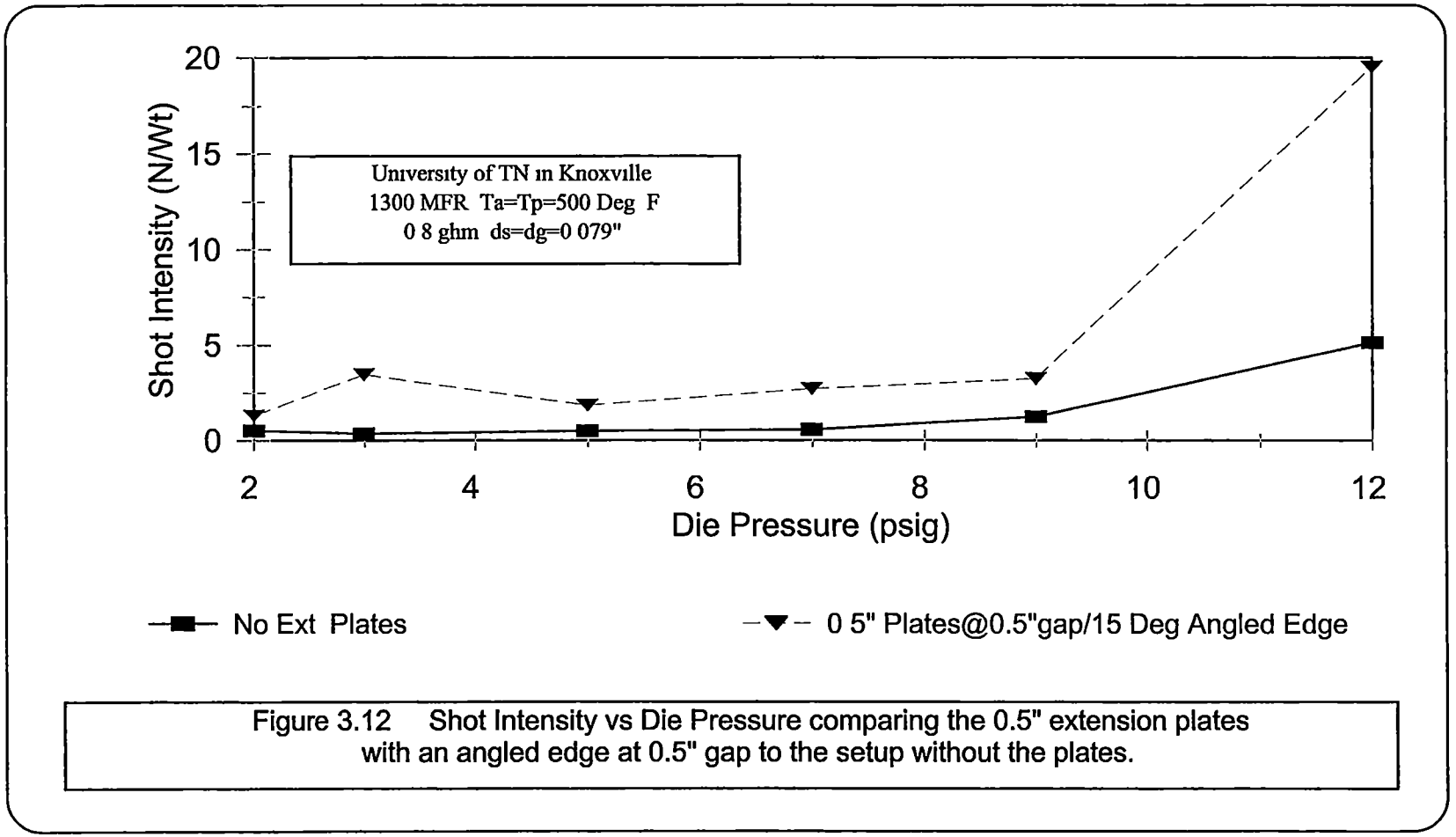


Figure 3.12 Shot Intensity vs Die Pressure comparing the 0.5" extension plates with an angled edge at 0.5" gap to the setup without the plates.

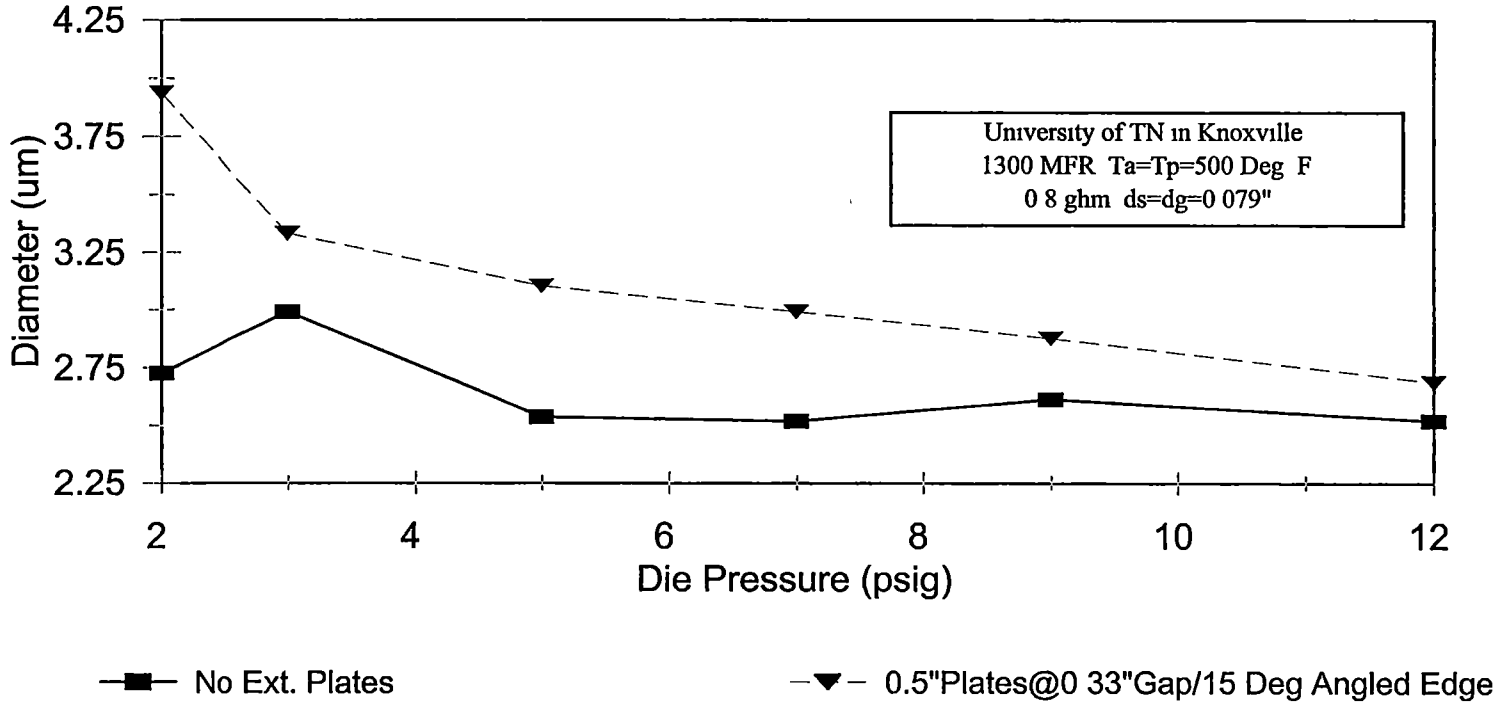


Figure 3.13 Diameter vs Die Pressure comparing the 0.5" extension plates with an angled edge at 0.33" gap to the setup without the plates.

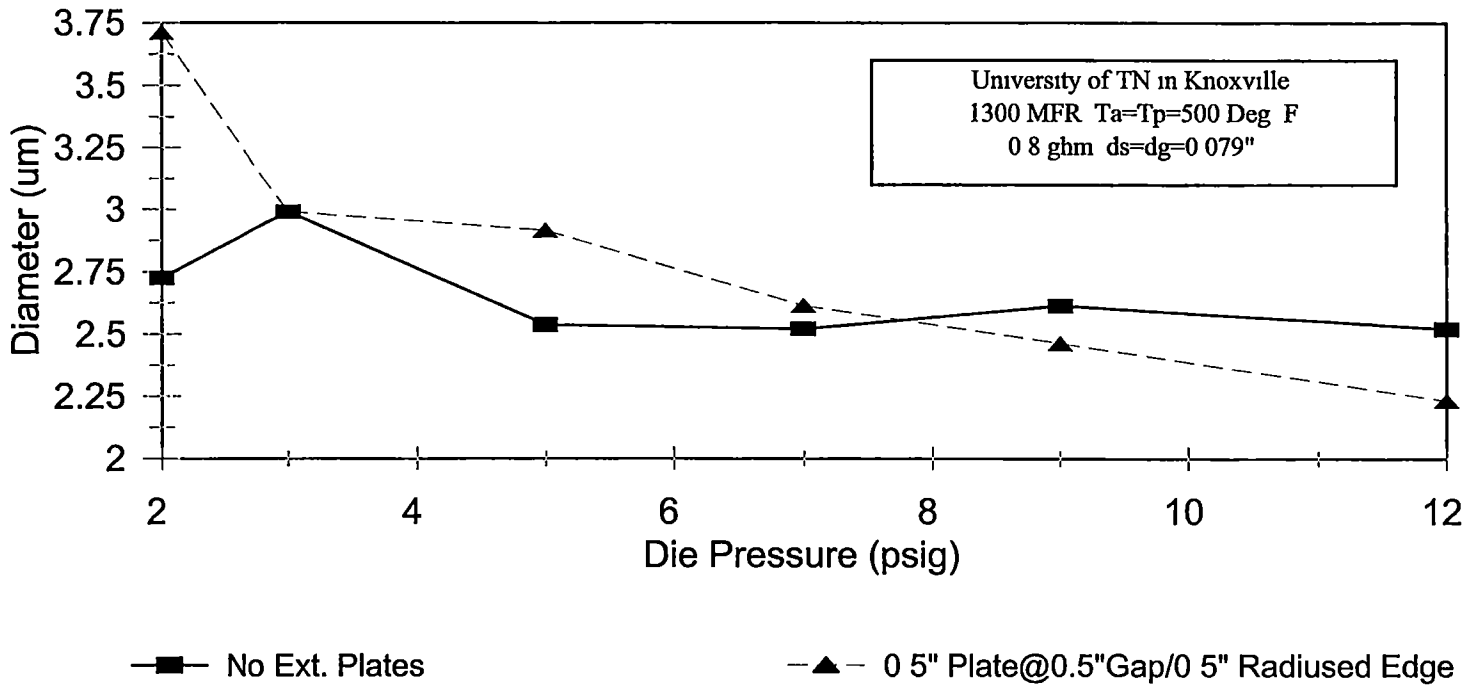


Figure 3.14 Diameter vs Die Pressure comparing the 0.5" extension plates with a radiused edge at 0.5" gap to the setup without the plates.

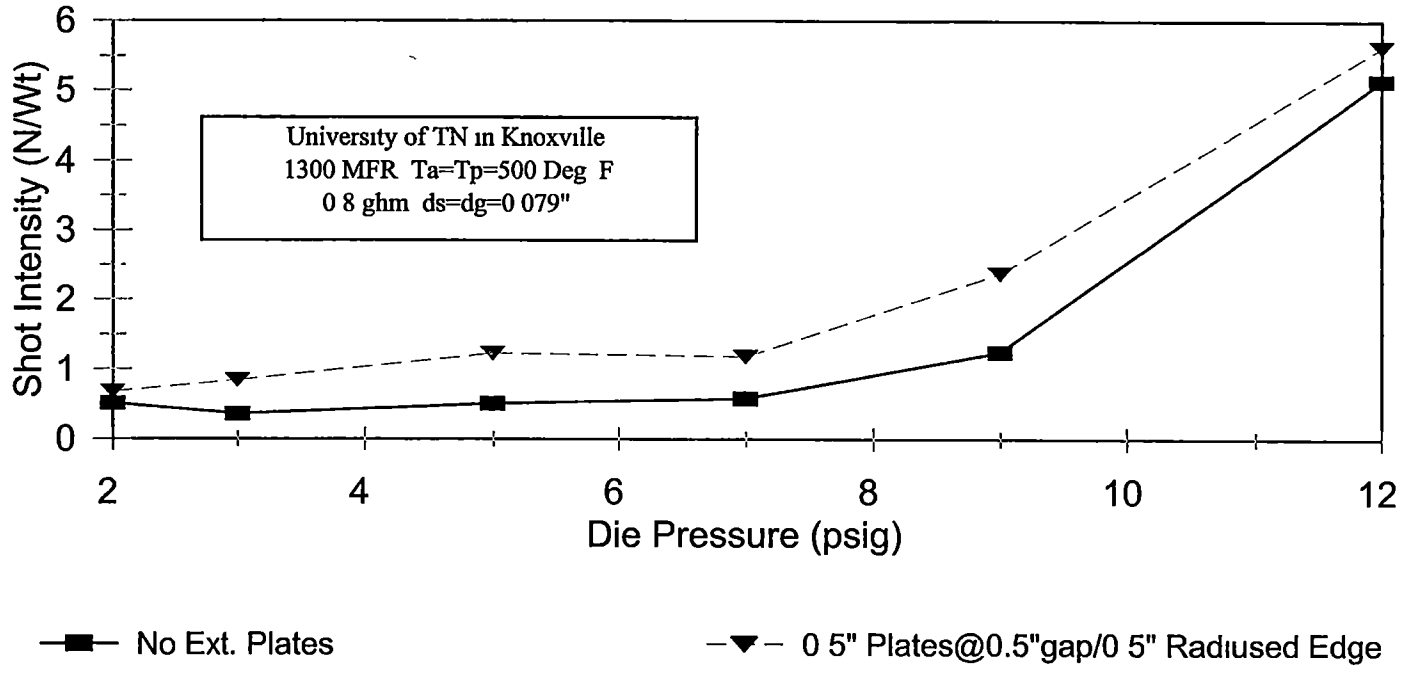


Figure 3 15 Shot Intensity vs Die Pressure comparing the 0.5" extension plates with a radiused edge at 0.5" gap to the setup without the plates.

These extension plates produce fiber diameters somewhat close to the case without any extension plates, but the shot intensity is much greater across the full range of pressures. This is similar to what happens with the 0.5" thick extension plates with the 15° angled edge. The final case is with the 0.5" radiused edge plates set at a 0.25" gap. As with the angled edge plates, the diameter information shown in Figure 3.16 demonstrates that there is a change in the airflow This change is not beneficial to the final web material and no shot analysis was done on these samples

At this point it is easy to see that in every case where the airstream is affected directly, the final web is changed at least somewhat. In most of the cases, the diameters increased when the constraint on the airflow is significant. Shot intensity values also increase, which indicates that the use of these extension plates causes the quality of the final web to decrease This could be due in part to the limitation of the flapping motion of the fibers close to the die since this movement aids in stretching them out. The loss of the entrained airflow could also affect the fibers and the stretching forces that they encounter. These experiments indicate a strong connection between the creation of small diameter fibers and the airstream close to the die From the cases where shot intensity was calculated, it is also evident that the extension plates cause a change to the final material. Because of these facts, it would be beneficial to study the airstream analytically to provide a better understanding of the forces involved in creating a web with fine fibers and minimal shot. Such a study of the turbulent jet flowfield would be very difficult to

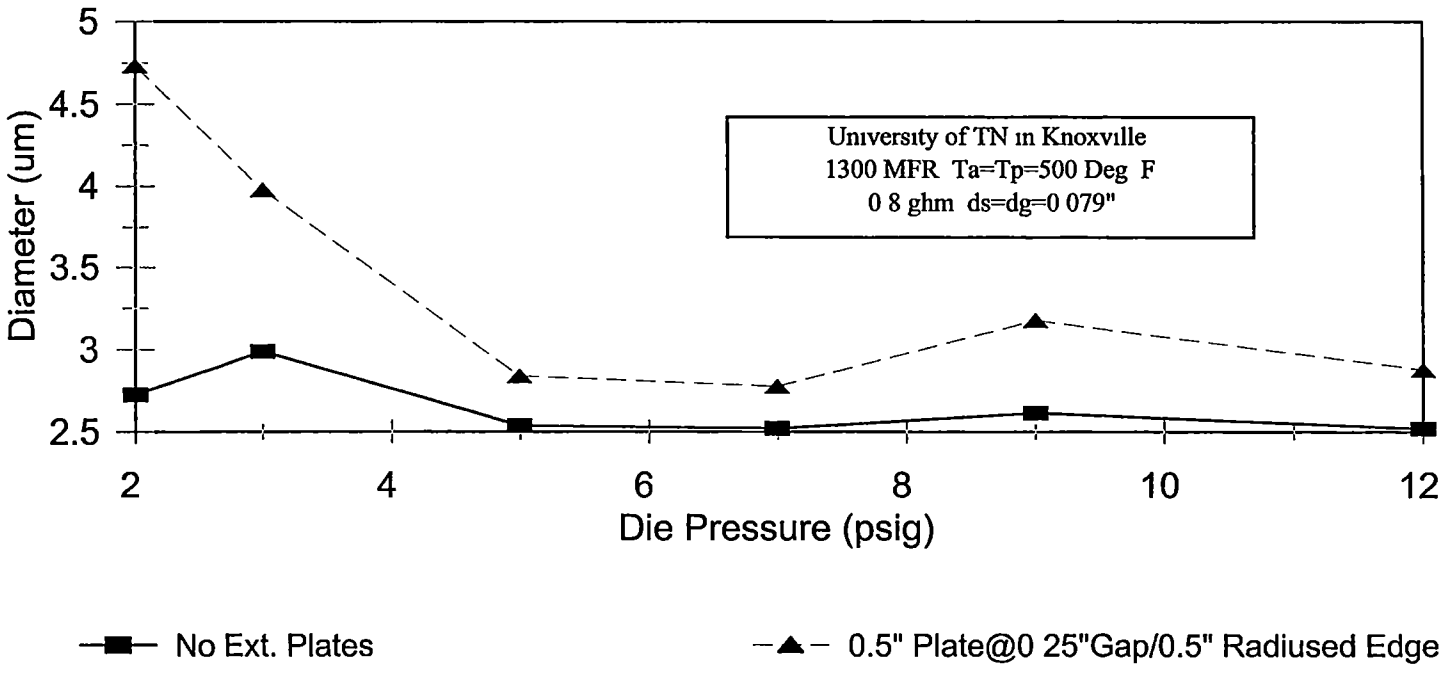


Figure 3.16 Diameter vs Die Pressure comparing the 0.5" extension plates with a radiused edge at 0.25" gap to the setup without the plates.

do, but would allow researchers to find a connection between the airstream and the final material Until such an analysis is accomplished, experimental work is necessary to find out how the melt blowing process can be improved.

Slit Die Design

An attempt was made to produce a more cost effective nosepiece design that could be produced easily and used to replace the existing designs All current nosepieces used in fiber melt blowing machines have tiny orifices drilled through them, in most cases by using a wire EDM process. This EDM process uses a single wire that is charged with a high voltage and is pushed through a grounded piece of metal The electricity causes the wire to cut into the metal and form a round hole or any other desired shape, depending on the movement of the block and the speed of the wire feed. It can be expensive to create a nosepiece for a machine that uses up to 30 holes per inch and is several inches wide. It is also quite difficult to produce consistent holes drilled into a block that are only 0.015" in diameter.

These problems led to the slit die design as shown in Figure 3.17. The design itself is easy to make and involves nothing more than using a long thin slit on the edge of the nosepiece instead of several holes. On the edge itself is a series of serrations above and below the slit Since the existing nosepiece with the maximum number of holes contained 30 in one inch, the length of the slit was set to just less than one inch in width with a total 26 peaks along the edge The slit was

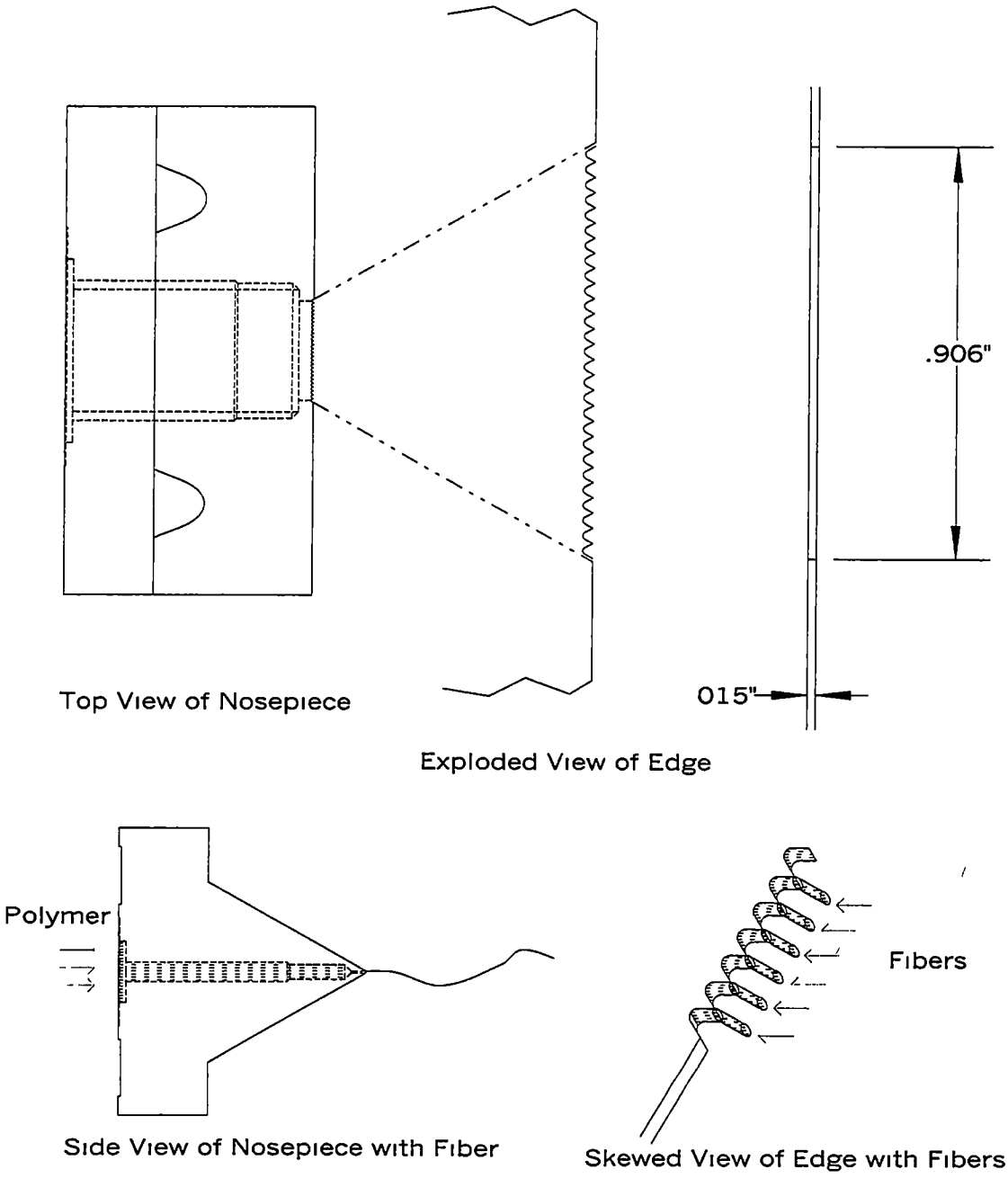


Figure 3.17 Alternate nosepiece design involving a narrow slit with a serrated edge.

cut all the way through the nosepiece so that the edge contains an opening that is 0.015" by 0.906".

The concept behind this design is a simple but innovative way to produce fibers. A solid layer of molten polymer flows through the nosepiece and is reduced down to a thin layer at the edge. As the polymer reaches the serrated edge, the surface tension of the liquid material causes it to adhere to the peaks and flow off the tips. This in turn will produce as many fibers as there are peaks. The individual fibers are then pulled out by the air and blown toward the collector as in the typical design

This design was tested in several ways by varying temperature, pressure, throughput, and die setback It should be noted up front that none of the collected samples were analyzed for either diameter or shot information. The nosepiece produced a very rough textured material that contained a considerable amount of shot that in some cases made the web material look like a solid film This is not to say that the design didn't produce fibers, but it was not a smooth flow coming from the peaks Initially, the machine was set at 500° F for both the air and polymer temperature with the die setback and gap at 0.079". The die pressure was then varied from 2 to 6 psig and the throughput set for 12 ghm and 23 ghm. This setup did seem to produce the best results The second experiment was with the same setup except for the air and polymer temperature which was changed to 400° F. The results were slightly worse than with the higher temperatures since the size of the fibers increased drastically The third and fourth experiments were at the same temperatures and pressures with the only change coming from the die setback.

This was changed to 0 0" which places the tip of the nosepiece right along the edge of the faceplates. Both of the experiments caused the amount of shot to increase along with the size of the fibers. In all of the experiments, the die to collector distance was kept at 16" which was considered to be the ideal for this design.

There are a few things to note from the experiments done with this nosepiece. The first and most noticeable observation that was made comes from watching the die as the machine is running The polymer did not flow smoothly from the peaks and there were many occasions where droplets of polymer were seen forming on the peaks and then blown off by the airflow. This caused most of the shot in the final web material. The next observation made comes from the change in the die setback. When the faceplates are placed slightly ahead of the nosepiece, the airflow comes together slightly in front of the edge. With the 0.0" setback, the airflow is concentrated right at the edge of the nosepiece. This shows that the air must be forced to flow between the peaks and that larger forces between the peaks will help improve the flow of polymer Another observation is found in the change in the air pressure which seemed to make some difference in the web material It was noted that when the pressure was increased, average diameters decreased but the amount of shot increased considerably. It is possible that the higher pressures caused the formation of droplets to increase along the peaks of the edge.

Such a new design is bound to have its problems, and there might be some ways to improve the quality of any web produced from this die Two things would help as seen in these experiments They are to improve the flow of the polymer through the slit and off the peaks and to improve the drag force on the fibers There

are several ways to improve the flow of polymer including reducing throughput, changing the geometry of the die and slit, and using a polymer with a higher melt-flow rate. A polymer that has a higher MFR would flow more smoothly and easily through the slit and off the peaks It is also necessary for the resin to maintain a high enough surface tension for the liquid resin to form at the peaks and not in between them Since it is desirable to have both a high MFR and a high surface tension, different resins might produce better results. It was discovered that having some die setback improved the final material over that produced with no setback. This indicates that the slit die design is sensitive to the small changes of the die geometry and would benefit from further experimentation in this area. It is also possible that the geometry of the peaks and valleys along the edge could be changed to aid in the creation of fibers from the edge of the slit Changes in the geometry of the slit might include the angle of the serrations or the distance between the peaks. Improving the drag force on the fibers by increasing the air pressure in the die decreased the fiber diameters but with a drastic increase in the amount of shot produced. This means that there is more required than just increasing the viscous drag on the fibers since it would result in material that is full of shot. Further experimentation is necessary to determine how the increase in air flow affects the resin at the edge of the nosepiece These ideas would need to be explored before this slit die design can be used in a commercial application.

Angled Hole Nosepiece

The final alternative die design studied was with another nosepiece that is slightly different from the original design. The basic configuration is similar to the standard 30 hole die with a 60° die angle. Since both nosepieces have 0.015" diameter orifices, the difference between the two comes from the way they are made. The standard 30 hole die has the holes drilled straight through along the centerline of the die. The angled hole die, however, has 30 holes drilled at 15° off the centerline starting from the center and pointing away from the center of the die The holes alternate in the direction that they are pointing. In other words, holes number 1, 3, 5, ., and 29 point 15° upward while holes number 2, 4, 6, . ., 30 point 15° downward. Figure 3.18 shows the arrangement of the holes drilled into the nosepiece. By angling the holes away from each other, the design should prevent the individual fibers from touching each other. This in turn might reduce the amount of shot seen in a web sample

Several experiments were performed with this nosepiece design that included changes in pressure, temperature and throughput. The initial experiment was designed to see how the new design reacted to a change in die air pressures The machine was set at a polymer and air temperature of 500° F with the die setback and gap at 0.079". The throughput was also set to 0.8 ghm for this run and the die pressure was varied from 2 to 12 psig. The next set of experiments looked at three different sets of temperatures (428° F, 464° F, and 500° F) two die

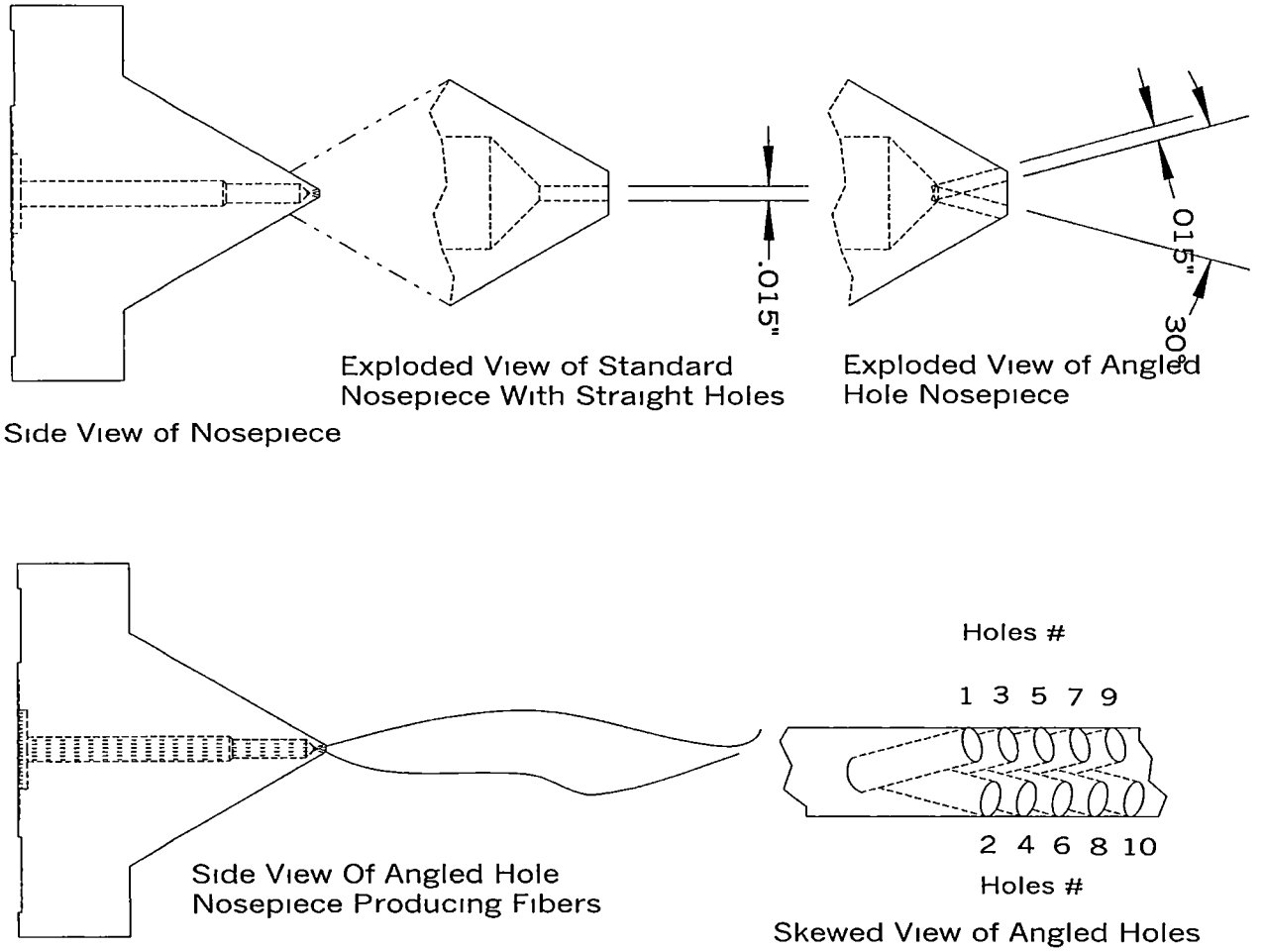


Figure 3.18 Alternate nosepiece design involving angled holes drilled into the edge.

pressures (5 psig and 8 psig), and two throughputs (0.4 ghm and 0.8 ghm) Again, the die setback and gap were placed at 0 079". Another set of experiments was accomplished by changing the die setback to 0" and then varying the temperature, pressure, and throughput as before In every case the die to collector distance was kept at 16" with a constant rotational speed of the drum

The first experiment was designed to compare the average diameters produced by the angled hole design with the standard 30 hole nosepiece Figure 3 19 contains the results from this experiment and the comparison to the standard nosepiece. There are no real surprises seen with the curves since they are well within the tolerance of the microscope measuring scheme. This indicates a similar performance in producing fiber diameters for both designs. It should be noted that no shot analysis was done for these samples since the next experiments were designed to look at that in some detail.

The next few experiments provide a general look at the die and how it responds to different variables. By first looking at the average diameter information gained from these experiments, one can see that the angled hole die piece shows no improvement over the standard one Figure 3.20 is from the 8 psig case with a throughput of 0.8 ghm and the die setback and gap placed at 0.079". This Figure compares the two designs at all three temperatures. Figure 3 21 compares the two at 5 psig with all of the other variables remaining the same. The next two figures are from the change in throughput. Figure 3.22 is at 8 psig and 0.4 ghm and Figure 3.23 is at 5 psig and 0 4 ghm. All of these figures show the general trend that the

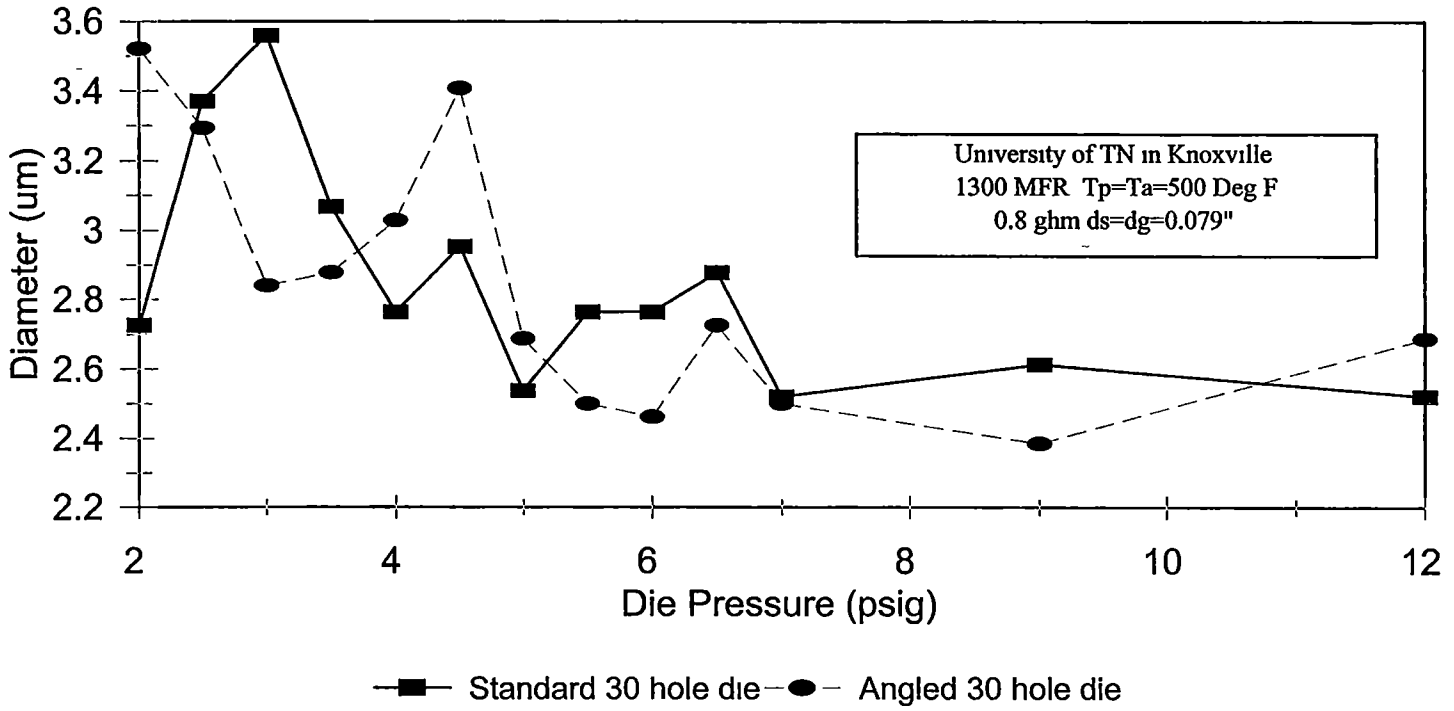


Figure 3.19 Diameter vs Die Pressure comparing the angled hole die design to the standard 30 hole design.

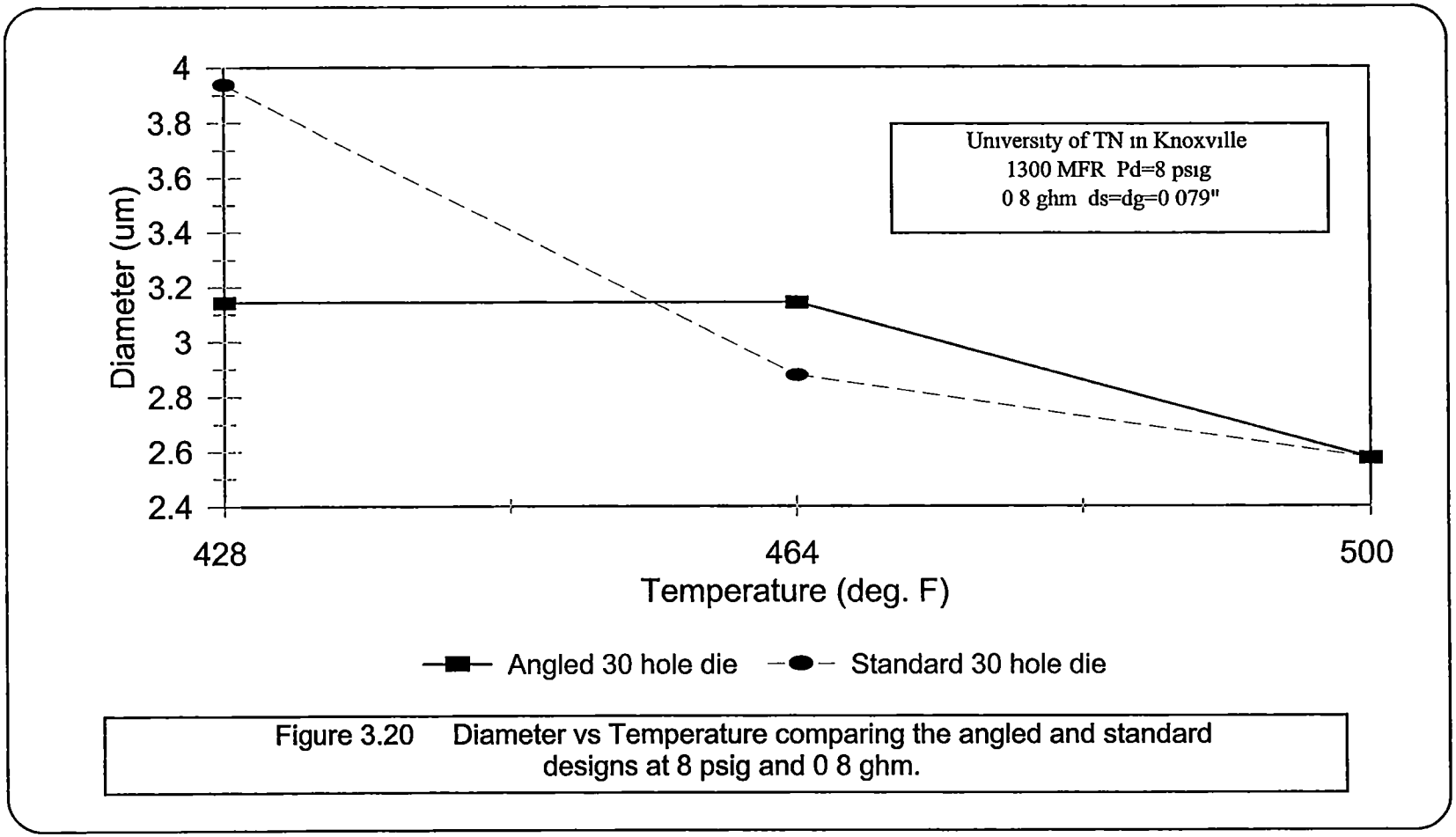


Figure 3.20 Diameter vs Temperature comparing the angled and standard designs at 8 psig and 0 8 ghm.

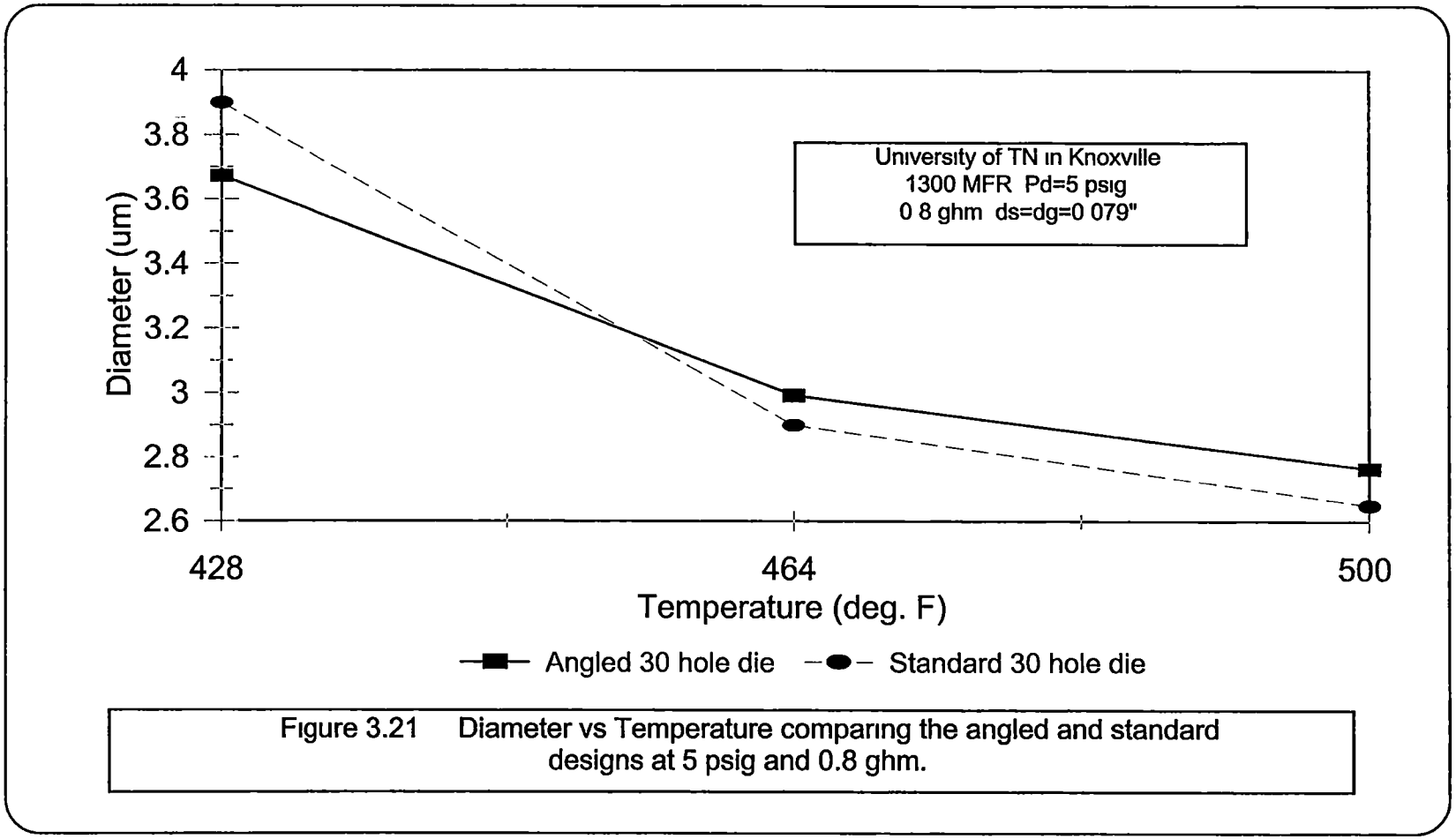


Figure 3.21 Diameter vs Temperature comparing the angled and standard designs at 5 psig and 0.8 ghm.

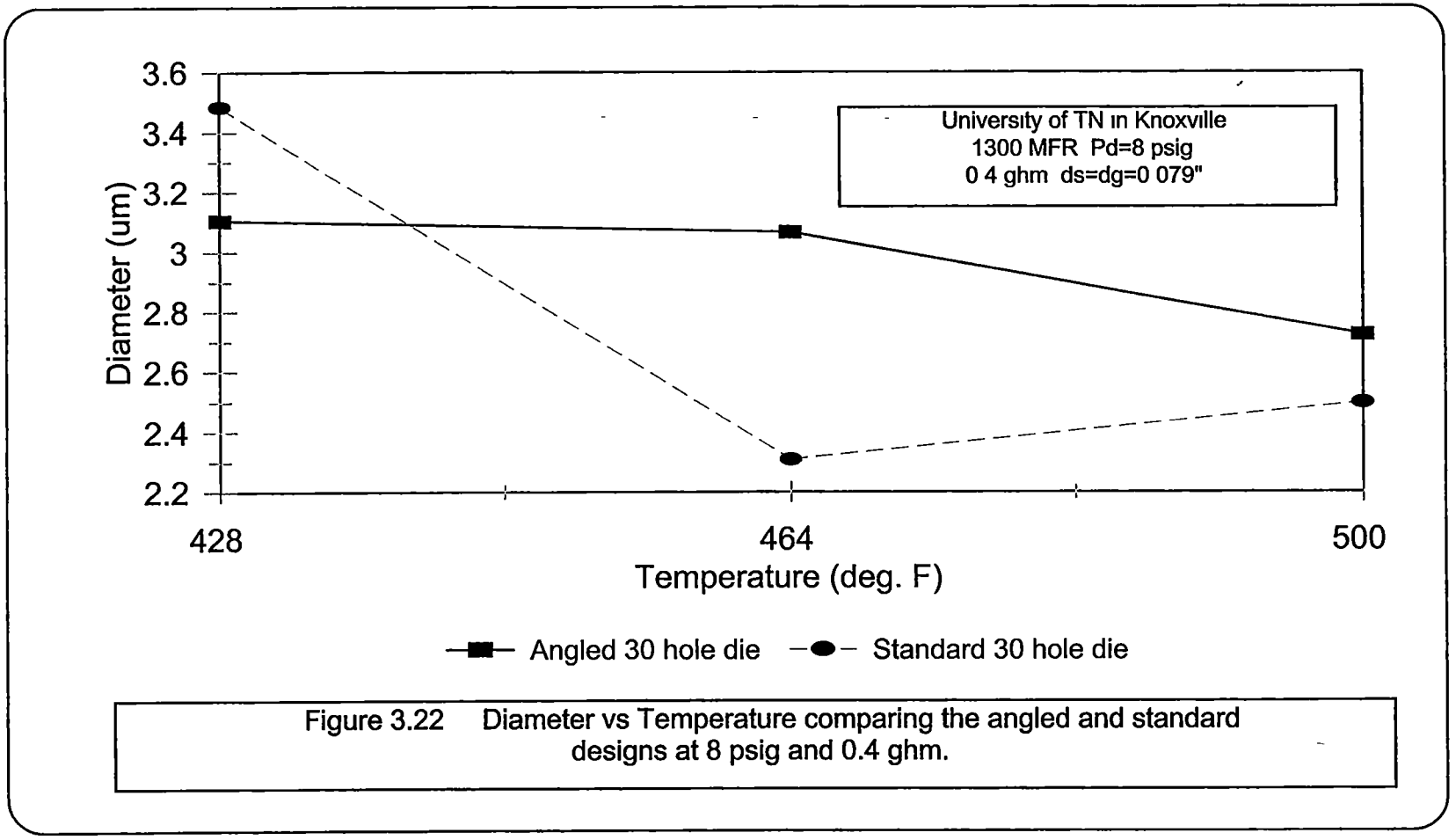


Figure 3.22 Diameter vs Temperature comparing the angled and standard designs at 8 psig and 0.4 ghm.

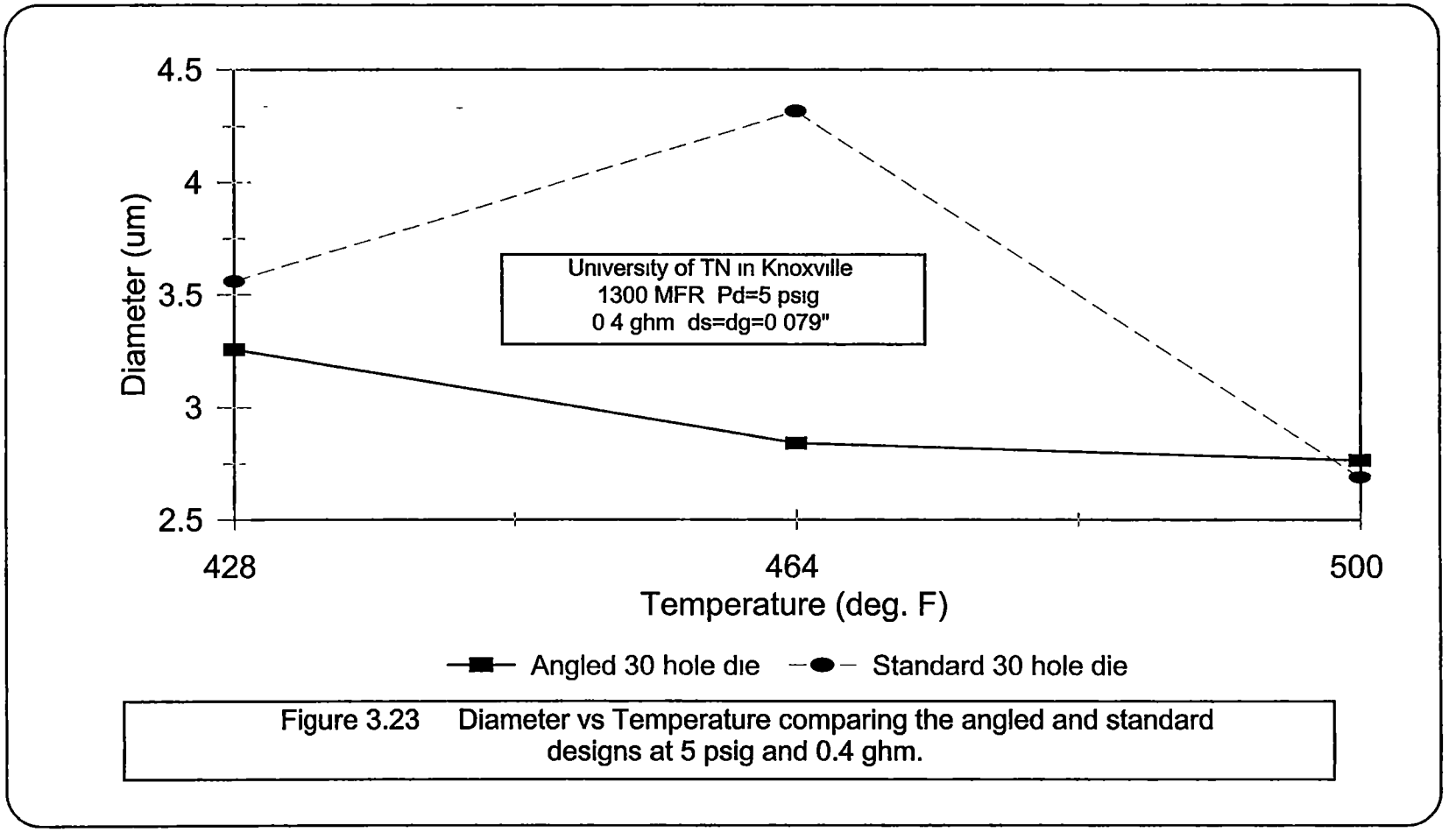


Figure 3.23 Diameter vs Temperature comparing the angled and standard designs at 5 psig and 0.4 ghm.

average fiber diameters decrease when the temperature increases. These results indicate no improvement with the new design since the values are close to those produced by the standard design and the differences are within expected variances

On the other hand, analysis of shot reveals several things about the new design It is important to note that these values are from WebPro which are in terms of shot per unit area. The figures are in the same order as before with Figure 3.24 containing the experiment at 8 psig and 0.8 ghm Figure 3 25 is with the die pressure changed to 5 psig Figures 3.26 and 3.27 are with the throughput at 0 4 ghm and the pressures at 8 and 5 psig respectively. The most noticeable thing that one can see from Figure 3.24 is that the amount of shot in the angled hole die samples is greater than from the standard die. Since the numbers are low, the amount of variance in WebPro might be part of the difference seen. In Figure 3.25, the numbers are close enough together to prevent any conclusions to be drawn at all. When the throughput is cut in half to 0.4 ghm, Figures 3.26 and 3.27 show that the angled hole die produced much less shot than the standard 30 hole design and in some cases the amount differs by a factor of more than 5.

The final set of experiments were with the setback placed at 0.0" and throughput, temperature, and pressure varied as before. The same three temperatures were used which are 428° F, 464° F, and 500° F The throughputs were 0.4 ghm and 0.8 ghm and the pressures included 3, 4, 5, and 7 psig. The change in the setback produced some interesting results that made some very rough material with a large amount of visible shot None of the collected samples

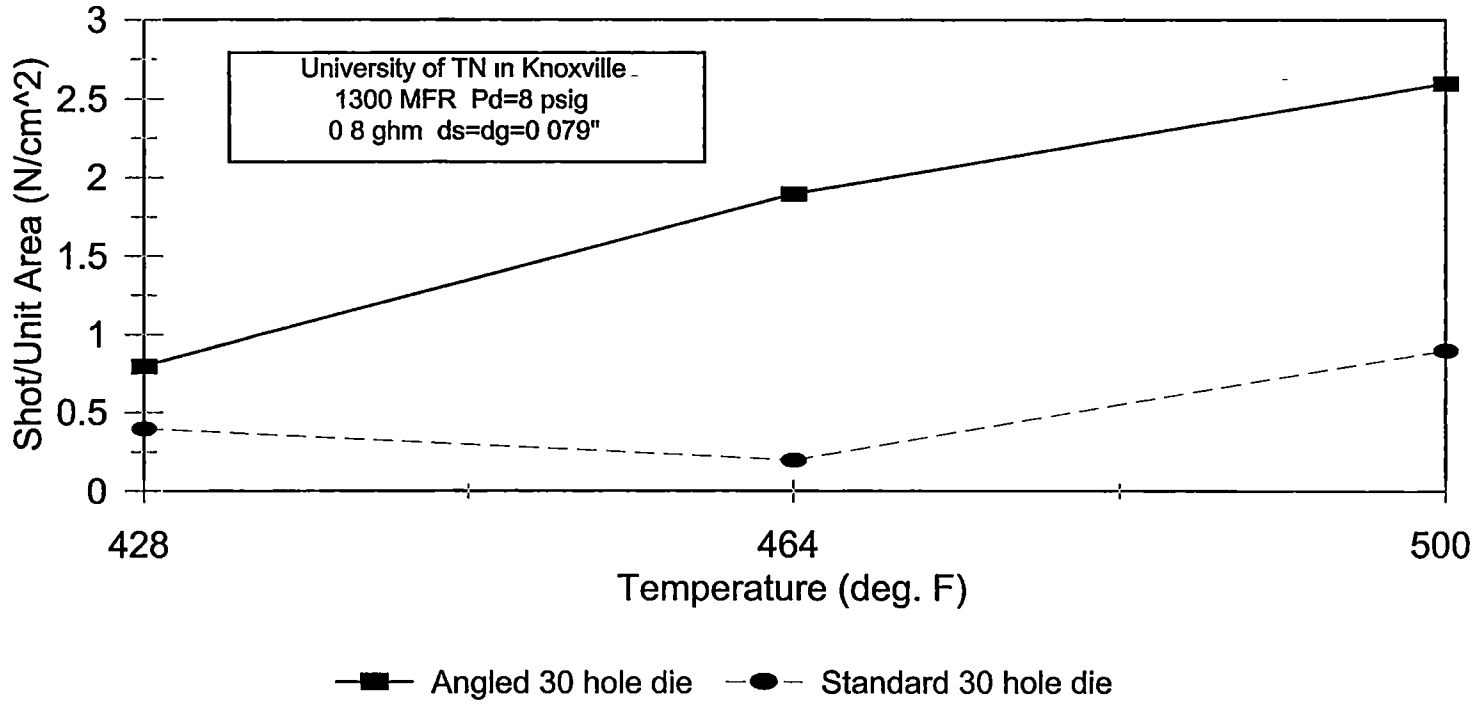


Figure 3.24 Shot/Area vs Temperature comparing the angled and standard designs at 8 psig and 0.8 ghm.

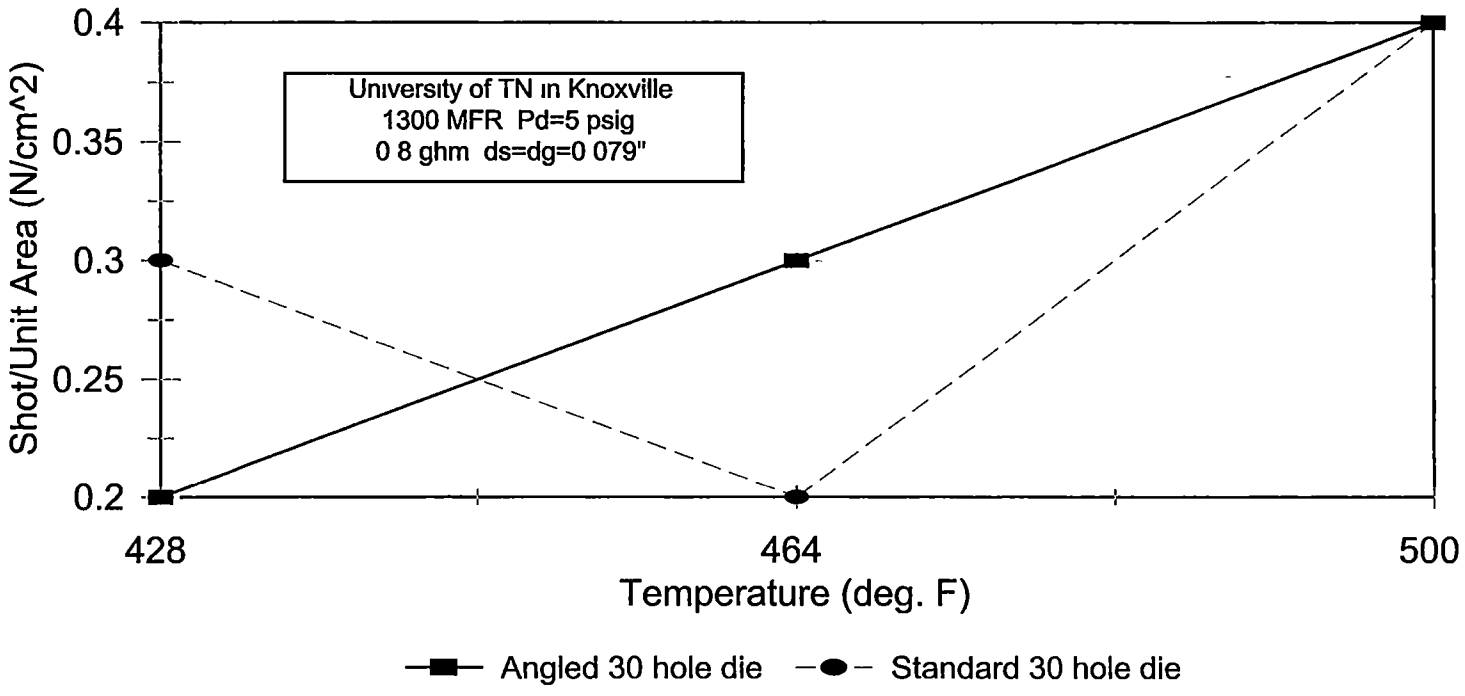


Figure 3.25 Shot/Area vs Temperature comparing the angled and standard designs at 5 psig and 0.8 ghm.

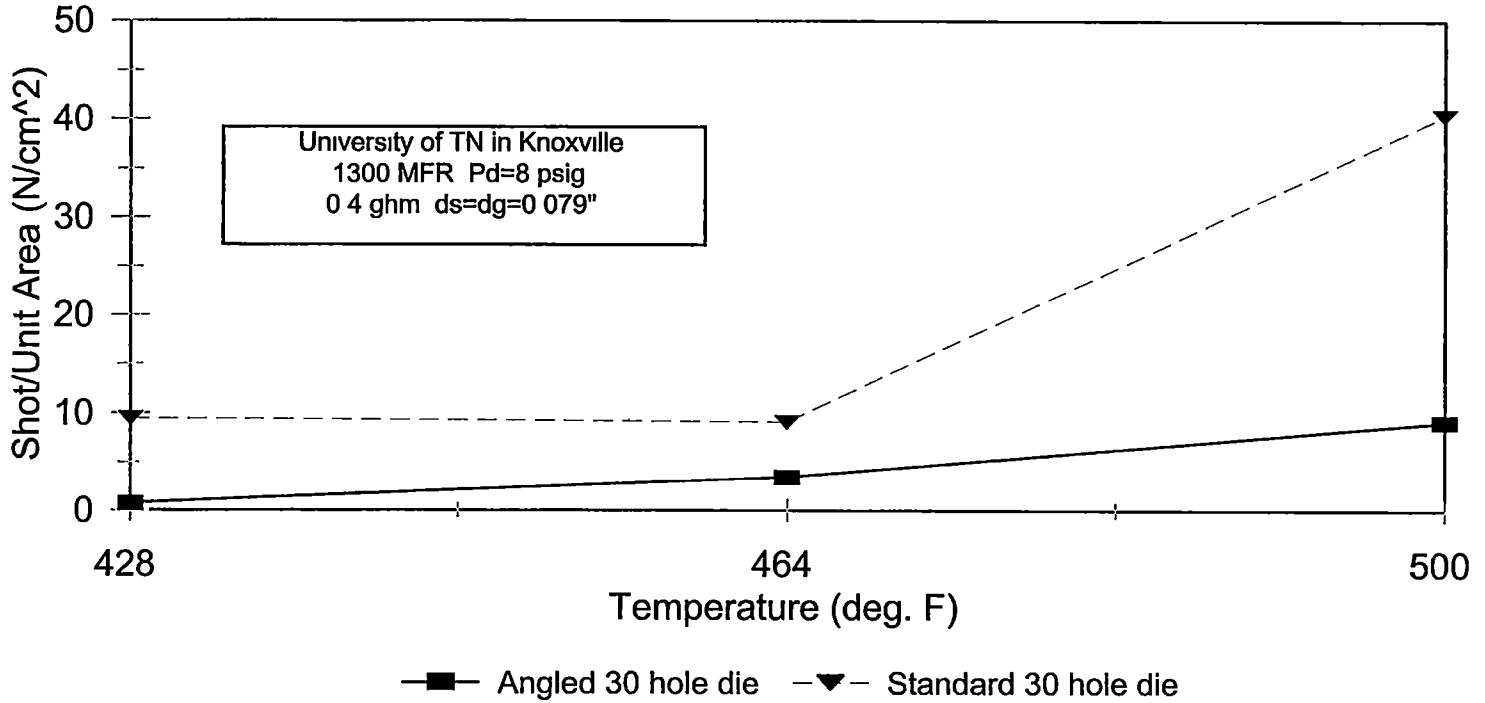


Figure 3.26 Shot/Area vs Temperature comparing the angled and standard designs at 8 psig and 0.4 ghm.

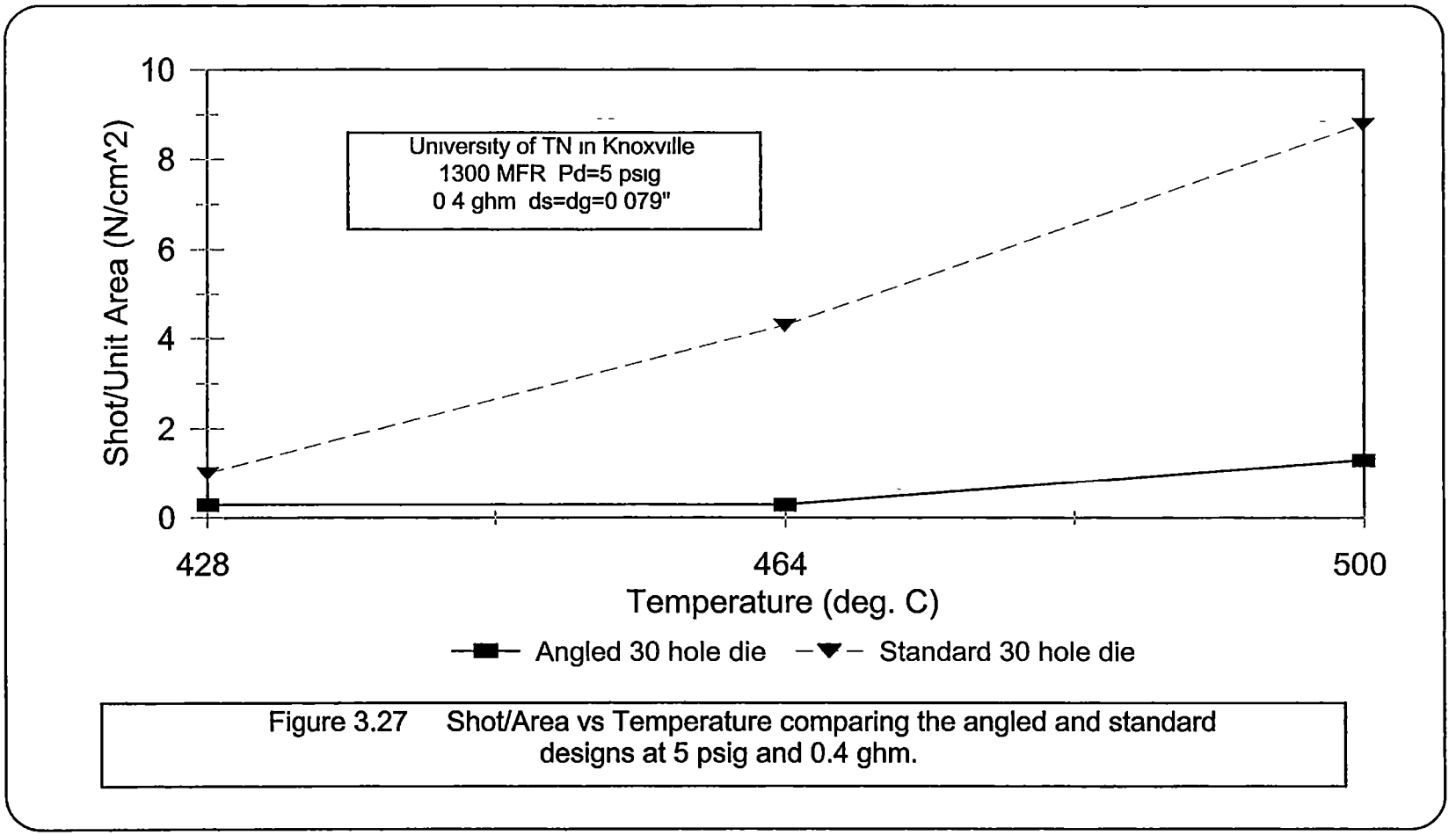


Figure 3.27 Shot/Area vs Temperature comparing the angled and standard designs at 5 psig and 0.4 ghm.

were analyzed for diameter or shot information since the material was much worse than what was produced with the standard design.

There are a few things that must be pointed out before any conclusions can be drawn from the angled design. The first comes from the way the holes are made in the nosepiece. The wire EDM machining process works better if the wire is pushed down into a flat surface that is perpendicular to the wire itself. This is obviously not the case when the holes are drilled into an edge at an angle This less than optimum situation of creating the tiny orifices along the edge caused them to be non-uniform in size and shape. It is very apparent by visually inspecting the holes and with a little magnification, one can easily see that there were several holes that were larger than 0.015" in size and more than one hole had an oval shape. There were a few holes that looked like they were not spaced equally with the others and the edges of the holes were spaced closer than the desirable distance.

Even with the problems associated with the holes in this new design, it did show some promising results. The average diameter information obtained during these experiments indicated that the angled holes do not have much if any effect on the diameters. The shot data on the other hand, indicated that the angled holes do influence the final web material. As stated before, the lower throughput caused the angled hole die to do what was expected of it. Even with the higher throughput, the amount of shot was not much if any worse than that produced by the standard 30 hole nosepiece The final set of experiments was where the non-uniform holes caused problems with the process. At 0.0" of setback, the airflow converges at the

edge of the nosepiece as it exits the die With a small amount of setback, the airflow converges in front of the edge of the nosepiece before it exits the die which will force the fibers toward the centerline of the die This was evident by examining the fibers while the machine was running in both the 0 0" setback case and the 0.079" setback case. When the setback was changed to 0 0", the fibers had a noticeably larger amount of flapping motion close to the edge of the die than with the 0 079" setback case. It is apparent that the combination of the increased flapping motion and the non-uniform holes caused the amount of shot to drastically increase when the setback was set to 0.0".

With this angled hole design, there are several promising results that warrant further experimentation. The first concern that needs to be addressed is the process for drilling the holes. If the orifices can be drilled out in a uniform way, then the molten polymer material would flow smoothly enough to produce more uniform and possibly smaller fibers. The next question to consider is how this alternate design reacts to the change in the setback. With further experimentation and even by filming the process with a high speed video camera, the die could be more closely examined to see how much the flapping motion increases when the setback is changed The last item would be to verify that the primary goal of the angled hole design is met. That goal is to decrease the contact between fibers as they fly from the die to the collector. One method to accomplished this is to use a high speed video camera focused on the fibers from the top and the side as they exit the die. If the fibers do not touch each other in the air as much with the use of this design, then further experimentation would prove if the touching of two or more fibers in the

air causes shot to be produced. By answering these questions and concerns, this new angled hole design could provide some improvement over the existing standard die designs.

At this time, there is no clear advantage to using the different die designs over the standard design with the 30 holes per inch nosepiece The extension plates only serve to worsen the overall characteristics of the web produced with them The slit die didn't even produce a viable web and the angled hole nosepiece was not consistent enough for manufacturing purposes. This leads back to the original die design that can produce webs that have average fiber diameters within 2 to 5 microns The standard layout can be adjusted to account for different materials and web thicknesses. Operating conditions (such as temperature, pressure, collector speed, etc.) can be varied to provide optimum web material for the intended applications. Of course, the correct polymer must also be selected to provide the desired web consistency

CHAPTER IV

SHOT FORMATION MODEL AND CONCEPTS

This chapter covers the basic concepts of shot formation and attempts to answer several questions surrounding the issue of shot found in the material produced by using the fiber melt blowing process The process of shot formation in melt blown webs is one of the least understood mechanisms that has been explained in various ways by many different researchers. As stated earlier, much of the research up until recently has been focused on the production of smaller average fiber diameters. This focus has been shifted toward understanding shot production in an attempt to improve the final quality of the web material Typically shot is reduced by using modern high MFR polymer resins and various other conventional means, such as lower temperatures. With modern test equipment, such as high speed video cameras, shot production can now be understood to the extent that the fiber melt blowing process can be modified to reduce this undesirable characteristic.

This chapter is divided into three sections with the first two presenting some of the information covered in a presentation by Milligan and Bogard [10] The first section is a brief look at what shot is and presents a broad model that best

represents the existing concepts behind shot production. The second section covers the different variables that influence shot production and will provide several possible ways to reduce shot. The third and final section will describe a series of experiments on a single hole die and how it relates to shot formation in melt blown webs The author believes that this section contains some remarkable results that shed some light on the whole issue of shot production.

Shot Formation in Melt Blown Webs

The basic issue of shot formation can be understood by first looking at what shot is. A few photographs of shot can be seen in the last section of this chapter As stated previously, shot is nothing more than imperfections in the fiber melt blowing process that can be found in the final web material. These defects cannot be completely eliminated but can be controlled through various means. Shot itself is considered to be a globule of polymer that is formed and adheres to the web during the process It is usually much greater in size than the surrounding fibers and can be large enough to be seen without any magnification. When shot is formed, the material that would normally be turned into a fiber becomes a solid formation on the web This can either form on the surface of the web and reduce the flow of fluid through the web in that area or it can actually melt the surrounding fibers to create a hole in the web. Either way, filtration efficiencies are reduced and the process must be altered to overcome this undesirable characteristic.

The two basic types of shot are a large mass (compared to the fiber diameters) of polymer that adheres to the web or one that forms a hole by melting the surrounding fibers in the web. The first type simply adheres to the web forms before it reaches the collector and is at least partially solidified when it comes in contact with the web. The second is large enough so that it does not solidify until it reaches the web In this case, it remains hot enough to melt the surrounding fibers and creates a hole in the web. Some of the larger pieces of shot are formed by droplets of polymer that collect on the edge of the nosepiece and are blown off by the turbulent air flowing past them This is caused by either the die having a leak or the orifices being partially blocked with contaminants which interrupt the flow of resin through the die. The shot caused by these problems with the die often create holes in the web material. This requires the die to be immediately torn apart, cleaned, and then tightly reassembled Die swell and a phenomenon called chugging which is a disruption in the smooth flow of polymer from the nosepiece, will also cause shot to be formed at the die. Die swell is a situation where the pressure of the polymer inside the nosepiece along with the heat of the die causes the nosepiece to expand. This expansion distorts the shape of the orifices and also disrupts the smooth flow of the resin Chugging can be caused by a number of factors, including partially blocked holes, or even insufficient throughput for a particular polymer. Chugging can usually be stopped by raising the temperature or throughput. All of the other pieces of shot are formed in the air as the fibers approach the collector The shot formed in mid-air are of special interest here since they represent the area that is least understood by researchers today

Milligan and Bogard [10] presented a broad physical model for shot formation that incorporates all of the existing concepts that are available up until now. This model is given as the following:

> VISIBLE SHOT IS FORMED WHENEVER THE DRAWING AND QUENCHING OF A MOLTEN FILAMENT IS DISRUPTED SO AS TO ALLOW MOLTEN AND/OR UNDER-DRAWN POLYMER TO REACH THE COLLECTOR SURFACE

As explained in Chapter II, visible shot is considered here as any piece of polymer that is larger than 100 microns in equivalent diameter found on the web. The concepts given in the above model incorporate most, if not all of the problems associated with the fiber melt blowing process and its processing parameters. In every case where shot is created, there is some type of disruption in the process where the filaments fail to be properly drawn out and reach the collector. These disruptions in the process will be further explored in the next section by looking at what influences the production of shot in melt blown webs.

Influence of Various Parameters on Shot Production

This section covers some of the basic parameters that influence shot production and shows what effect they have on it. The first such parameter is the die pressure which is directly related to the die exit air velocity and strongly influences fiber diameter and shot production. The second and third parameters are the die and air temperatures, which are often equal but can be varied

independently. Throughput is another parameter that can influence the amount of shot found in the web material and this will be explored through experimentation A fifth parameter that is easily varied is the polymer MFR. New polymers have been created with higher MFR ratings to address several concerns including shot production in melt blown webs These five parameters have been explored in the past and researchers on this subject have some understanding of how they influence the production of shot. The collector is also something that does influence the final web characteristics, yet it has not been studied extensively. The distance of the collector from the die is one parameter that can easily be changed and has been considered to some extent. One experiment will cover this issue more thoroughly. Finally, the surface of the collector can have an impact on the web material since the fibers hit it with a certain amount of force. Another experiment addresses this surface impact.

The first parameter to be considered is that of the die air pressure. It is important to note that Utsman [4] considered this and other parameters and their relationship to shot production. He found that by increasing air pressure, shot intensity decreased for any given polymer and air temperature. He noted this characteristic for pressures up to 12 psig This may be the case for lower pressures, but as seen in several of the figures in Chapter III the higher pressures cause the shot intensity values to go up dramatically. Figure 4.1 shows the collection of shot intensity data for all of the extension plates In every case, the amount of shot found in the web material increased at higher pressures, which is different from what Utsman [4] found This difference will be explained in the next

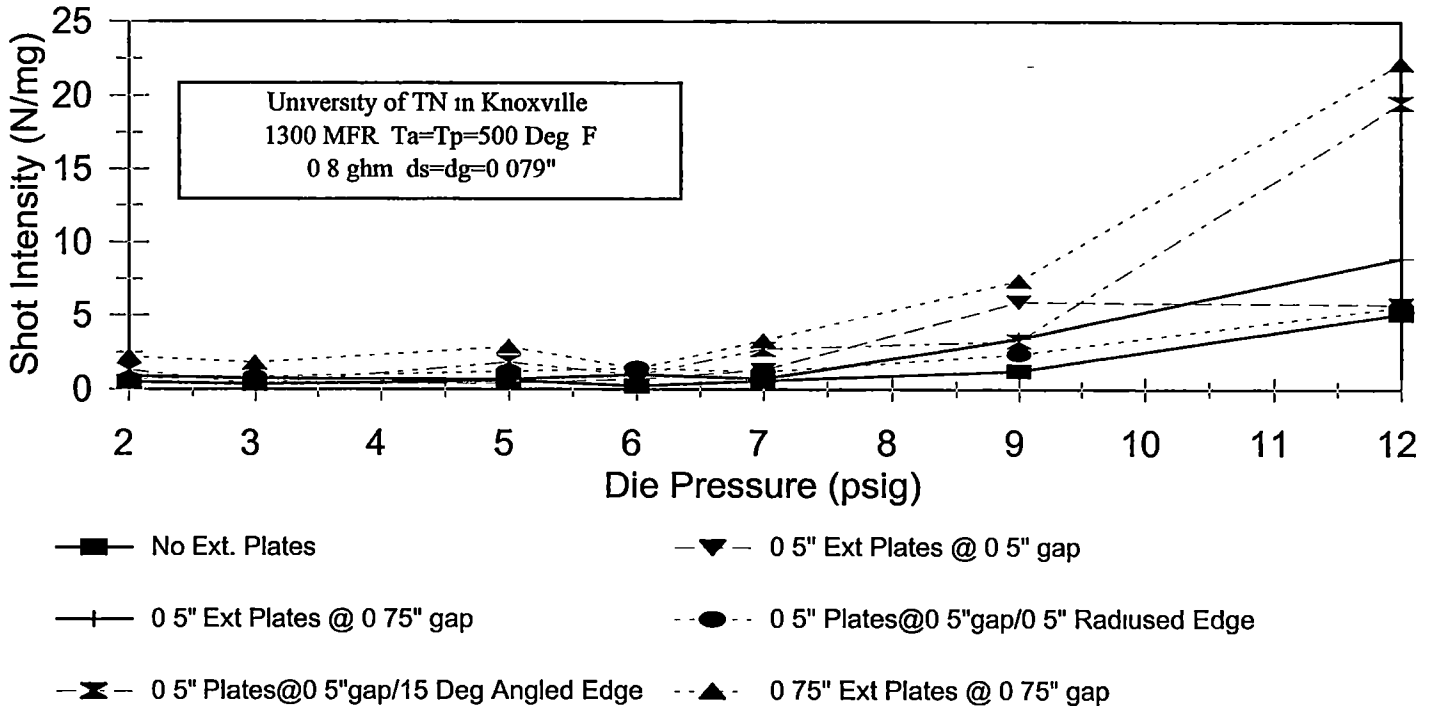


Figure 4.1 Shot Intensity vs Die Pressure for all of the extension plate cases from 2 to 12 psig.

section of this chapter.

By varying both air and polymer temperatures, shot can also be reduced. Utsman [4] also explored this; and found that by holding the polymer temperature constant, shot intensity would decrease as the air temperature was lowered. This was also the case for holding air temperature constant and varying the polymer temperature. Figure 4.2 contains some data that shows what happens to the shot intensity values when the air and polymer temperatures are varied independently. This information comes from a study of another polymer on the 30 hole, 60° die It is apparent that the amount of shot increases with increased air temperature, however, this is not as apparent with the polymer temperature. This could be due in part to the fact that the polymer temperature was not varied as widely as the air temperatures. It is generally understood that changing the temperatures affects the amount of shot and that shot can be reduced by lowering either one. It does, however, come at a price since lower temperatures create larger fiber diameters as seen in Figure 4.3. This figure indicates that lowering polymer temperatures will create larger fiber diameters. Air temperatures did not influence these samples as much, however, other experiments have shown that the air temperature will influence the fiber diameter as well.

It is generally accepted that changing throughput will influence shot production, but it is not clear what the connection is between the two. An experiment was done to investigate the question of how throughput influences shot. The 30 hole, 60° die was used with the die setback and gap at 0.079". The air and

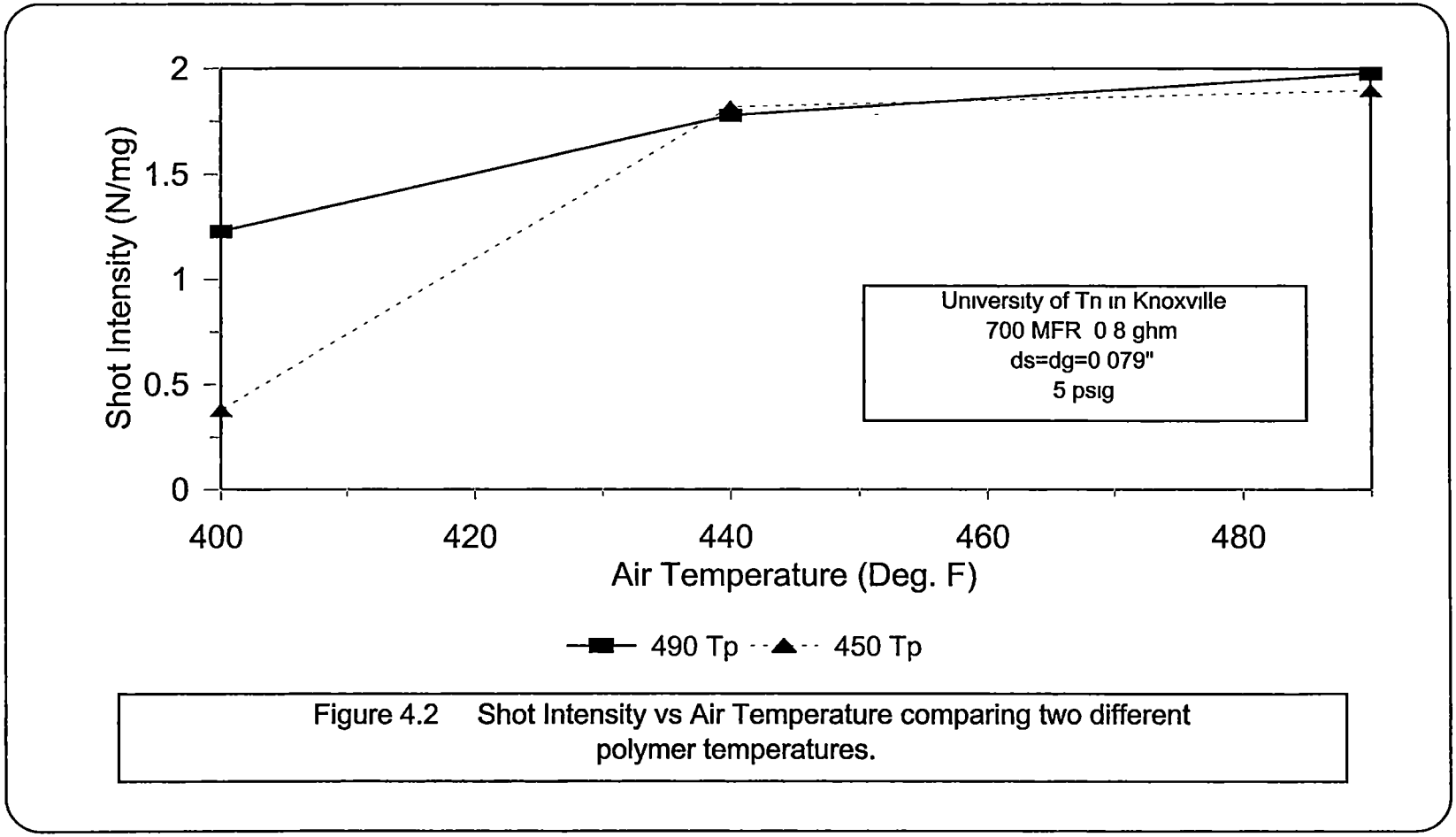


Figure 4.2 Shot Intensity vs Air Temperature comparing two different polymer temperatures.

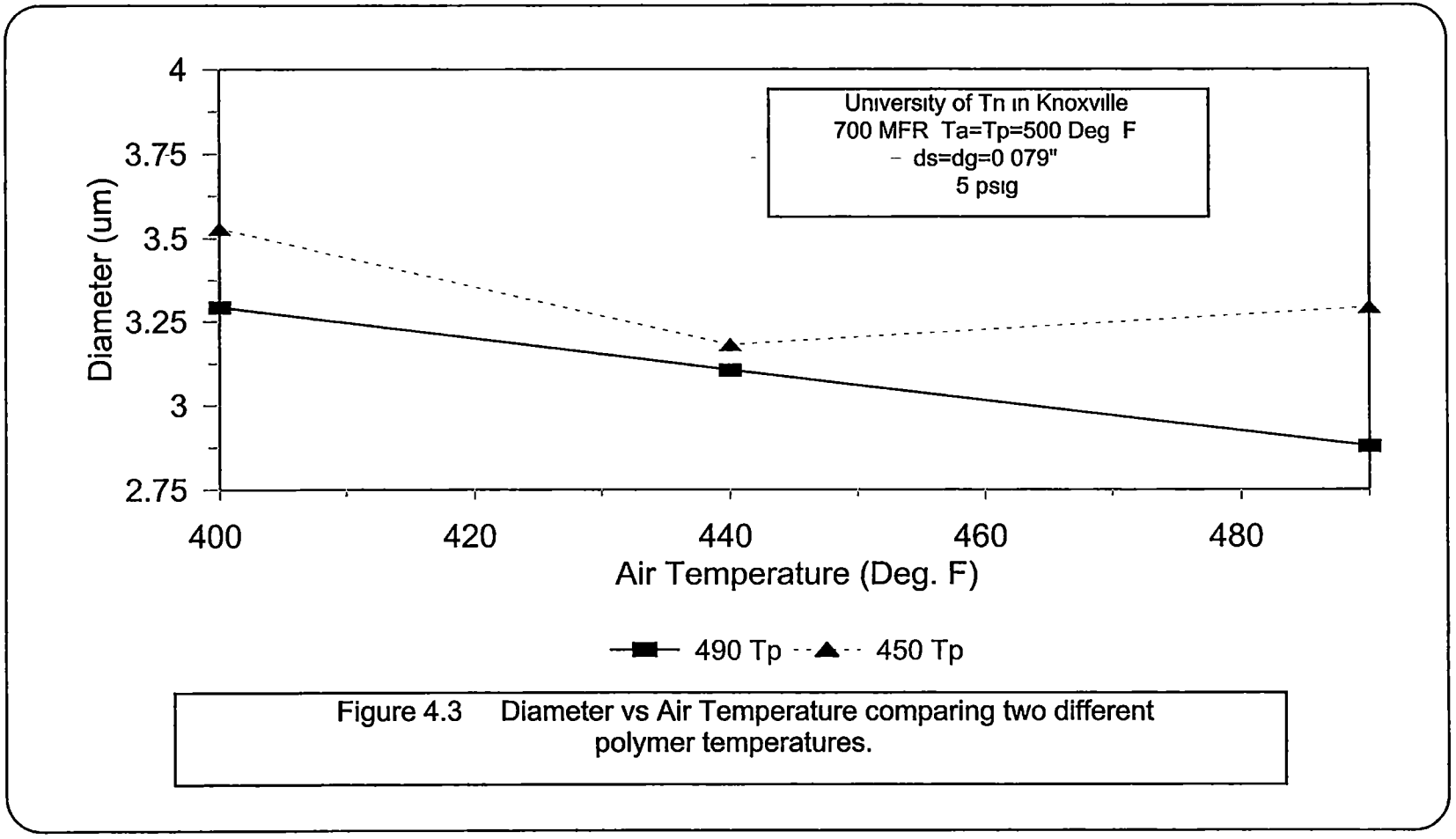


Figure 4.3 Diameter vs Air Temperature comparing two different polymer temperatures.

polymer temperatures were set at 490° F with the die pressure held at 5 psig These conditions were held constant along with the die to collector distance which was set at 16". Only two things were varied for this experiment which were the throughput (for 0 4, 0.6, 0.8, 1 0, and 1 2 ghm) and the collector speed. The collector speed was varied to ensure that web basis weight remained constant for analysis purposes. Figure 4 4 indicates what happens to the diameters and Figure 4.5 contains the shot intensity data. Nothing can be said about the fiber diameters since the variations between the points are well within the tolerances of the microscope measuring scheme. What is rather surprising is what the shot intensity information demonstrates. At first it would seem that the amount of shot increases as the throughput decreases, but there are other factors involved that must be considered.

By trying to produce web samples with a uniform basis weight and slowing the collector speed down to accommodate lower throughputs, shot was allowed to build up more in the final material. If shot is produced and covers the web material at a specific rate, then there would be more shot in the web material that is collected at slower speeds as shown in Figure 4 6a. If the collector speed is increased, then the same amount of shot would be spread out through the web as shown in Figure 4.6b For this experiment, the amount of shot produced at 0 4 ghm might not be much different than that produced at 0.6 ghm If this is the case, then the shot would build up faster in the web at the slower collector speed used for 0.4 ghm and there would be a higher shot intensity value for the lower throughput. This would

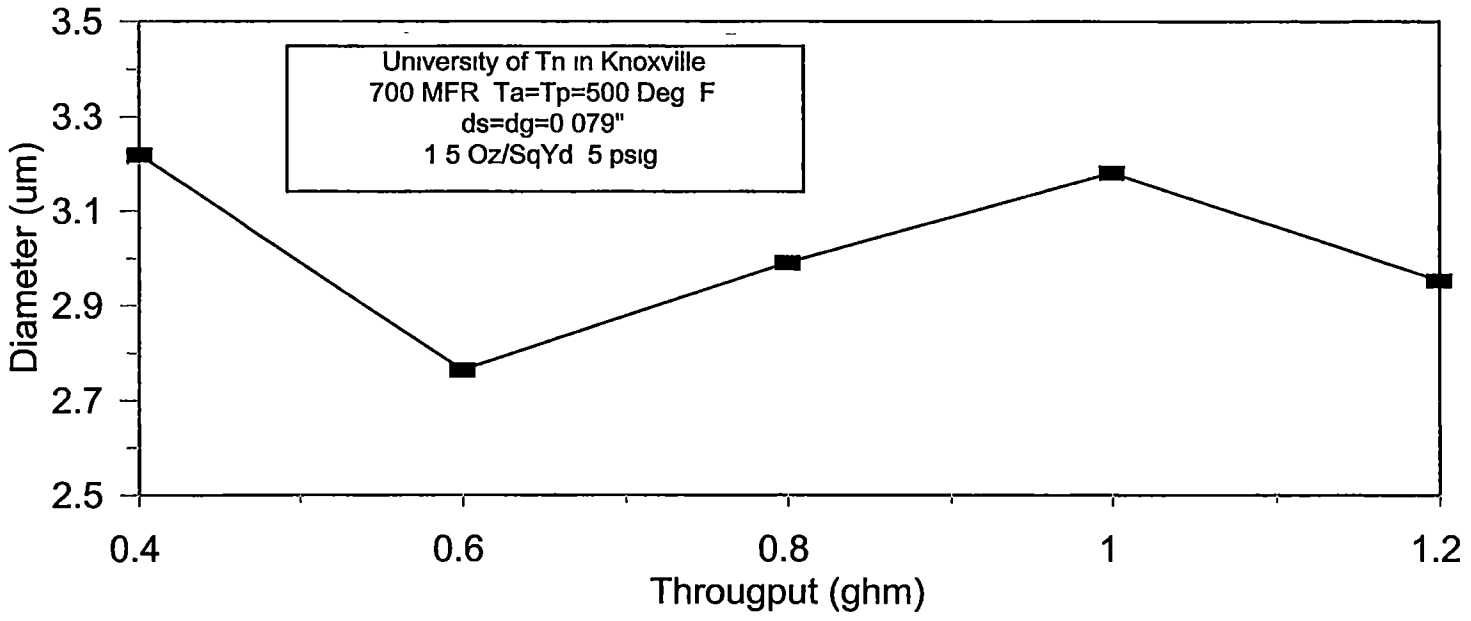


Figure 4.4 Diameter vs Throughput for the throughput variation test.

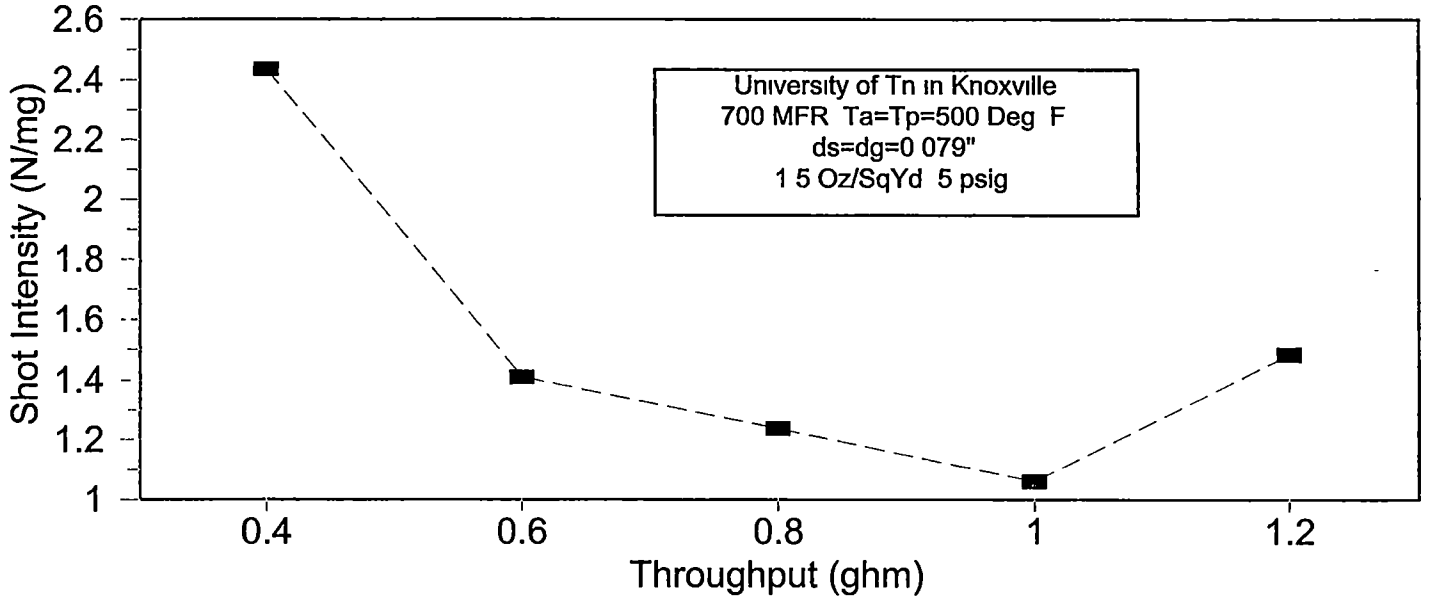
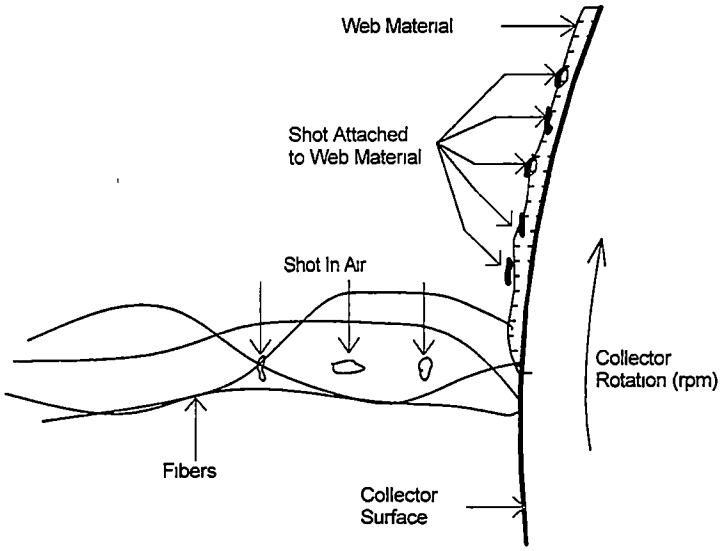
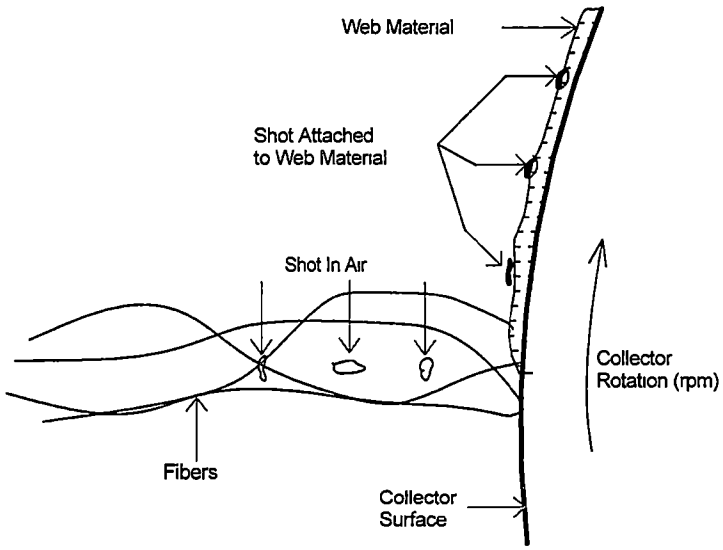


Figure 4.5 Shot Intensity vs Throughput for the throughput variation test.



4 6a Web Production at Slow Collector Speed



4 6b Web Production at Fast Collector Speed

Figure 4.6 Web Production at Various Collector Speeds

mean that the number of shot produced per unit of mass will increase with lower throughput The fact that the amount of shot produced does not necessarily change with time by varying throughput, indicates that it is possible to reduce shot by modifying throughput and the speed of the collector.

There are two other areas that should be considered when changing throughput. The first comes from the fact that individual fibers flapping in the air must have enough time to solidify before reaching the collector If throughput is increased, then each fiber must have more time to solidify to account for the extra material If the fibers are not solidified before reaching the collector, then the molten material will burn holes in the web and create shot. Figure 4 5 does show that shot intensity begins to increase between 1 0 N/mg and 1 2 N/mg. There is one other thing that could cause this increase and that is a phenomenon called die swell which occurs at all throughputs Heat and pressure cause the expansion of the nosepiece and subsequently the size of the orifices along the edge would increase as well. As throughput increases, pressure inside the nosepiece increases and die swell should be evidenced by finding larger fiber diameters in the web and possibly more shot. Since the fiber diameters do not vary significantly in this experiment, it isn't possible to tell anything about die swell here The slight increase of shot at 1.2 ghm more than likely comes from having more material in each fiber than what can solidify before it reaches the collector Further experiments with a constant collector speed and with throughputs up to 1 6 ghm, would provide more concrete information on how throughput affects shot production and whether die swell becomes a problem with higher throughputs

Polymer MFR is another parameter that is often changed to produce the type of melt blown material desired. Of course there are many other characteristics of polymer resins that are changed to influence the production of the web material Chemicals can be added in various amounts or the resin could even be processed in a different way By considering two somewhat similar resins with MFRs of 700 and 1300 from the study described in the next section, then it can be easily seen that a significant change in MFR results in a large difference in shot intensity values A polymer with a higher MFR will generally produce less shot which is demonstrated in Figure 4 7. This figure compares the two resins at various temperatures with both polymer and air temperatures held constant Again, there are many other factors that influence shot production as far as the resin material is concerned and it is not sufficient to say that only MFR is changed in these two resins

The collector also influences the production of shot in at least two ways and the first of which is the distance that it is placed from the die The die to collector distance has a direct impact on the production of fine fibers and the amount of shot found in the web since it determines how much time the fibers have to cool down Average fiber diameters can be reduced by moving the collector closer to the die, however the amount of shot will increase By moving the collector further away, the situation is reversed with a decrease in shot but with an increase in diameters. With less distance, fibers will receive less time for quenching and the collector is exposed to greater temperatures which causes it to get hotter. The combination of these two factors causes the conditions necessary to create more shot by preventing the fibers from having enough time to cool down An experiment was done to

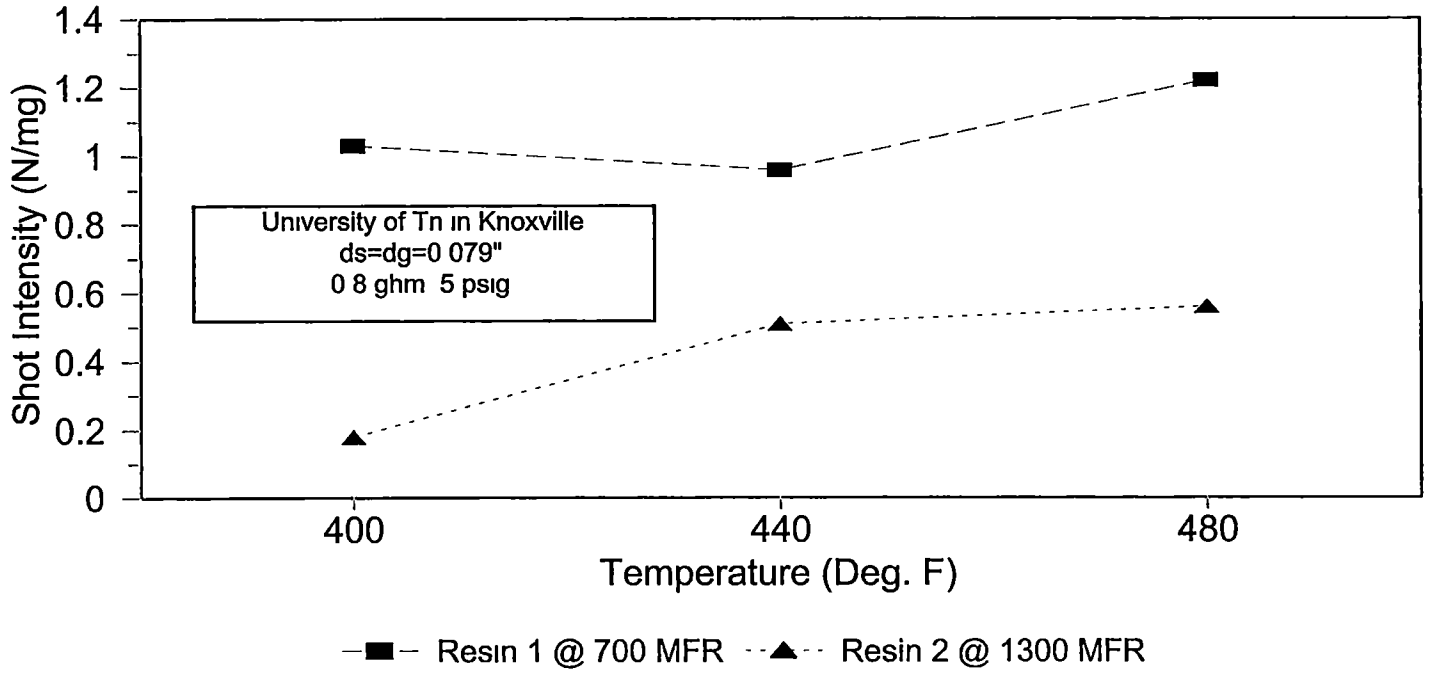


Figure 4.7 Shot Intensity vs Die Temperature comparing two polymers with different melt flow rates.

investigate this situation by varying only the collector distance while keeping all of the other variables the same The 30 hole, 60° die was used with the typical die setback and gap of 0 079" This was combined with an air and polymer temperature of 464° F, a die pressure of 5 psig, and a throughput of 0 8 ghm Figure 4.8 shows an increase in fiber diameters as the collector is moved away from the die and Figure 4 9 shows a decrease in shot. There were two runs for this experiment with the first one seen in Figure 4 8. The values generated for Figure 4.9 are from the second run at the same processing parameters but included several other collector distances for more detail on shot intensity. The trends seen here with the change in the distance of the collector to the die indicate that both fiber diameters and shot production can be controlled by moving the collector This is a relatively easy change to make and can alleviate some of the problems associated with shot production.

The second way that the collector can influence the die comes from the type of surface that the fibers are blown up against. It is usually made up of a fine wire mesh screen that will allow air to pass through it while trapping the fibers on the surface. One experiment was based on the assumption that a hard surface causes shot to flatten out which will create larger and more visible pieces in the material. The experiment was set up with the standard 30 hole, 60° nosepiece, an air and polymer temperature of 500° F, and a throughput of 0 8 ghm. The die to collector distance was set to 16" and a range of die pressures were run between 3 and 9 psig. Two different collector configurations were used The first was with the

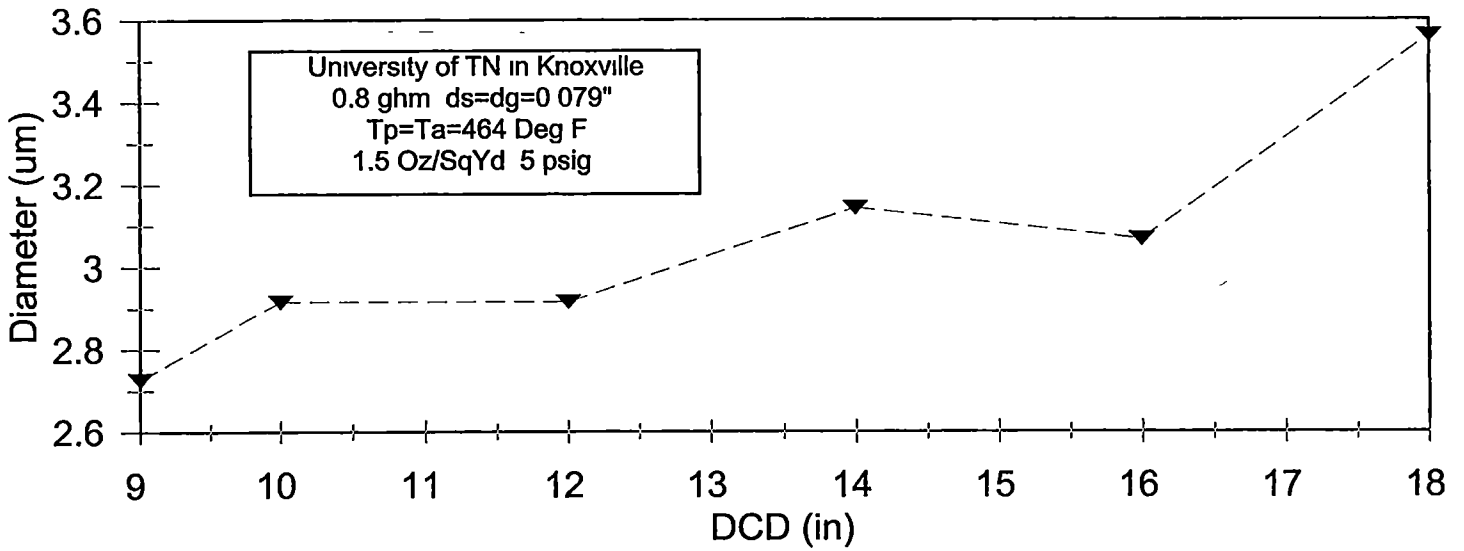


Figure 4.8 Diameter vs DCD and all other conditions held constant.

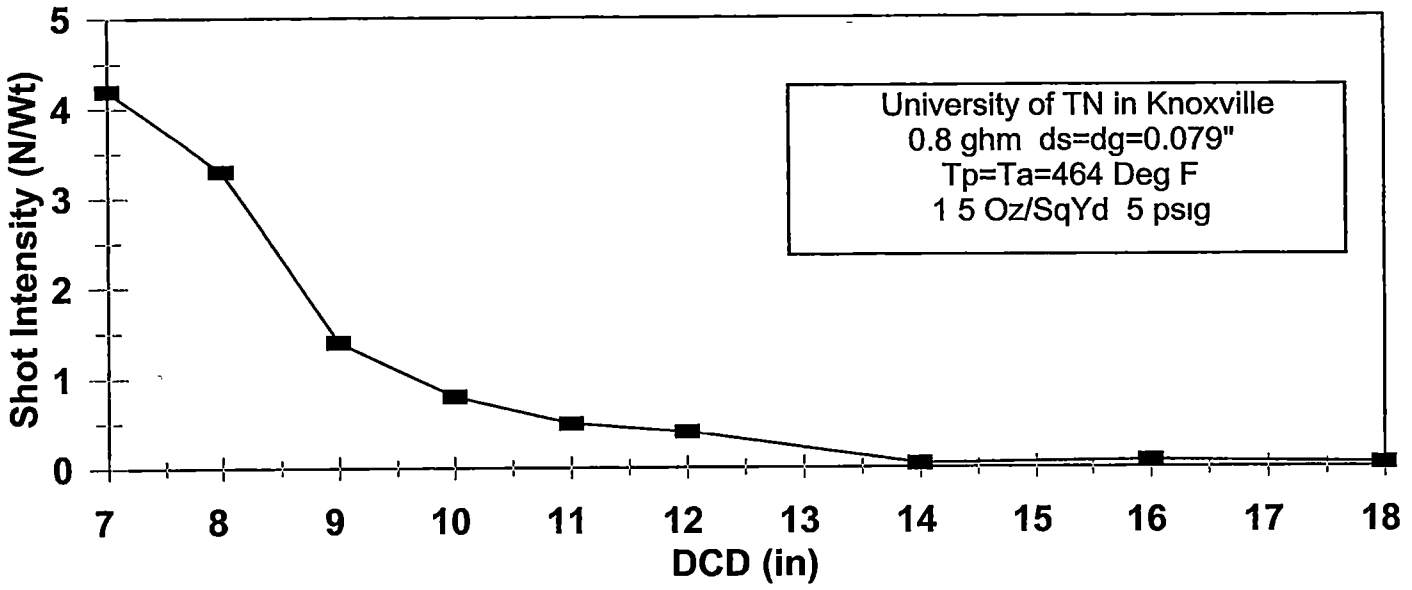


Figure 4.9 Shot Intensity vs DCD with all other conditions held constant.

collector covered with a soft heavy cotton material and the second was without anything on the collector. The average diameter information is presented in Figure 4.10. The only thing that is evident here is that the padding prevents the fiber diameters from decreasing as the pressure is increased. Four samples were then analyzed using Webpro with the results seen in Figure 4.11. This data strongly suggests that shot is flattened out when it hits a harder surface. Another study was done on the Webpro verification tests to support this conclusion by counting shot on each side of the web individually. That is, shot was counted on the side of the web laying up against the collector and another count was done on the side away from the collector. Figure 4.12 shows the results for the 2.5 Oz/SqYd basis weight and Figure 4 13 contains the information for the 1.0 Oz/SqYd case There is a remarkable difference between the two sides as far as the amount of shot is concerned. It should also be apparent that the thicker samples appear to contain less shot indicating that the build up of fibers on the surface offers some padding to prevent shot formation.

It should be evident by now that there are several methods for reducing shot formation in melt blown webs. Some of which can include reducing temperatures, changing throughput and collector speed, or by changing die air pressure. Other methods for reducing shot can include using a higher MFR polymer, moving the collector further from the die, or by providing a softer collector surface. The results of these experiments support the model given by Milligan and Bogard [10] by showing that shot can be reduced by improving the process of creating small

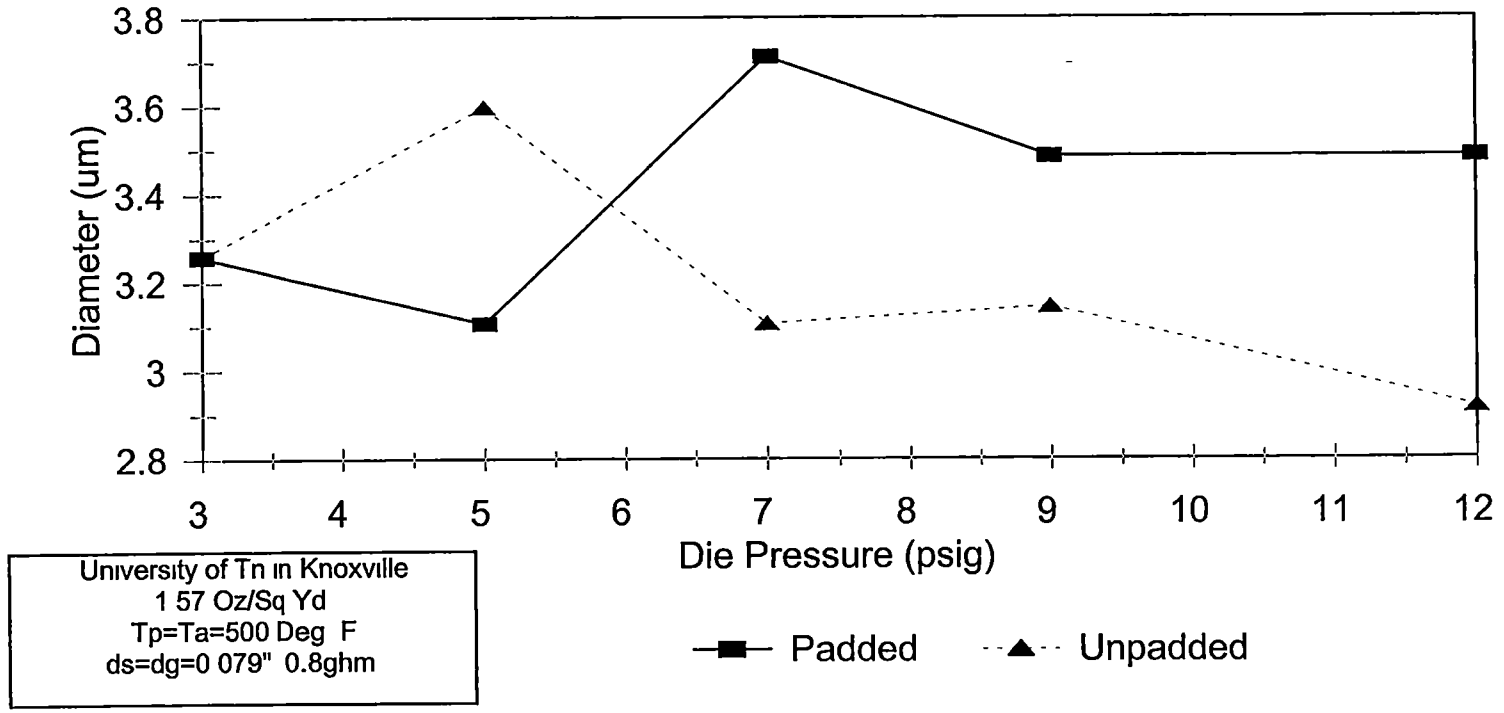


Figure 4.10 Diameter vs Die Pressure for the padded die test.

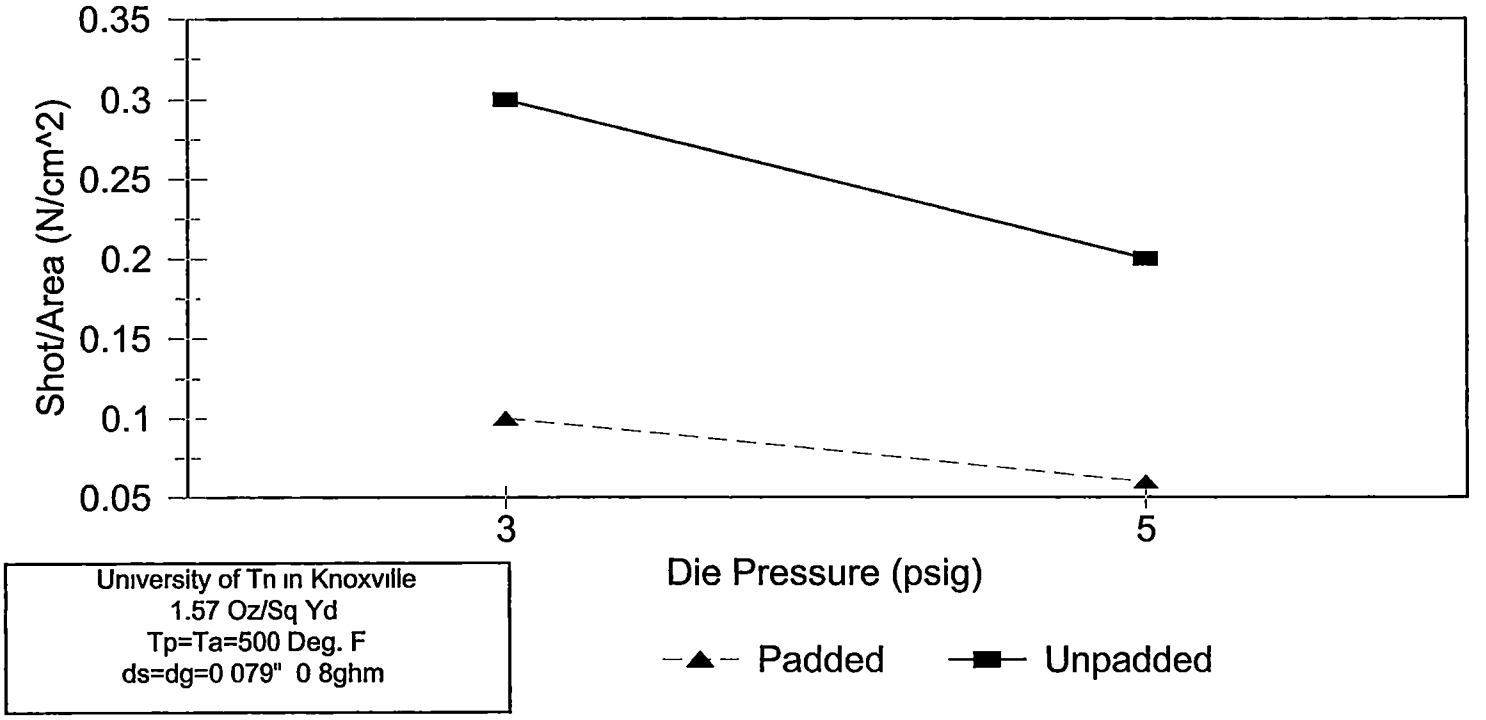


Figure 4.11 Shot/Area vs Die Pressure for the padded die test.

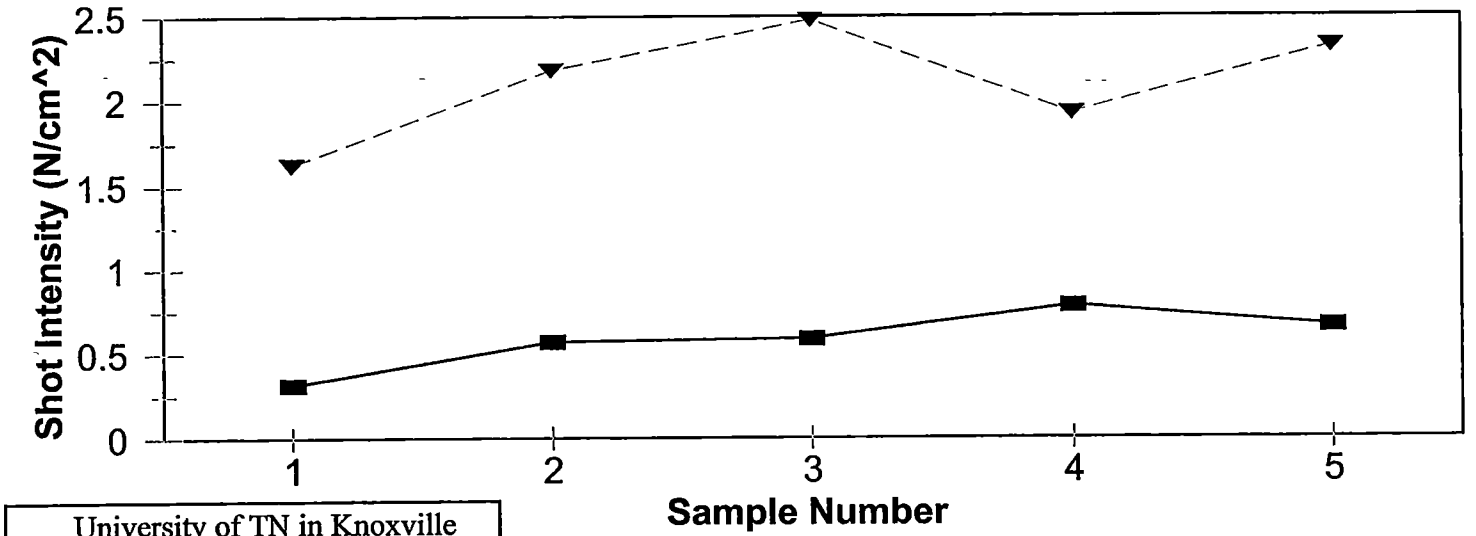


Figure 4.12 Shot Intensity vs Sample Number comparing the two sides of the web @ 2.5 Oz/SqYd.

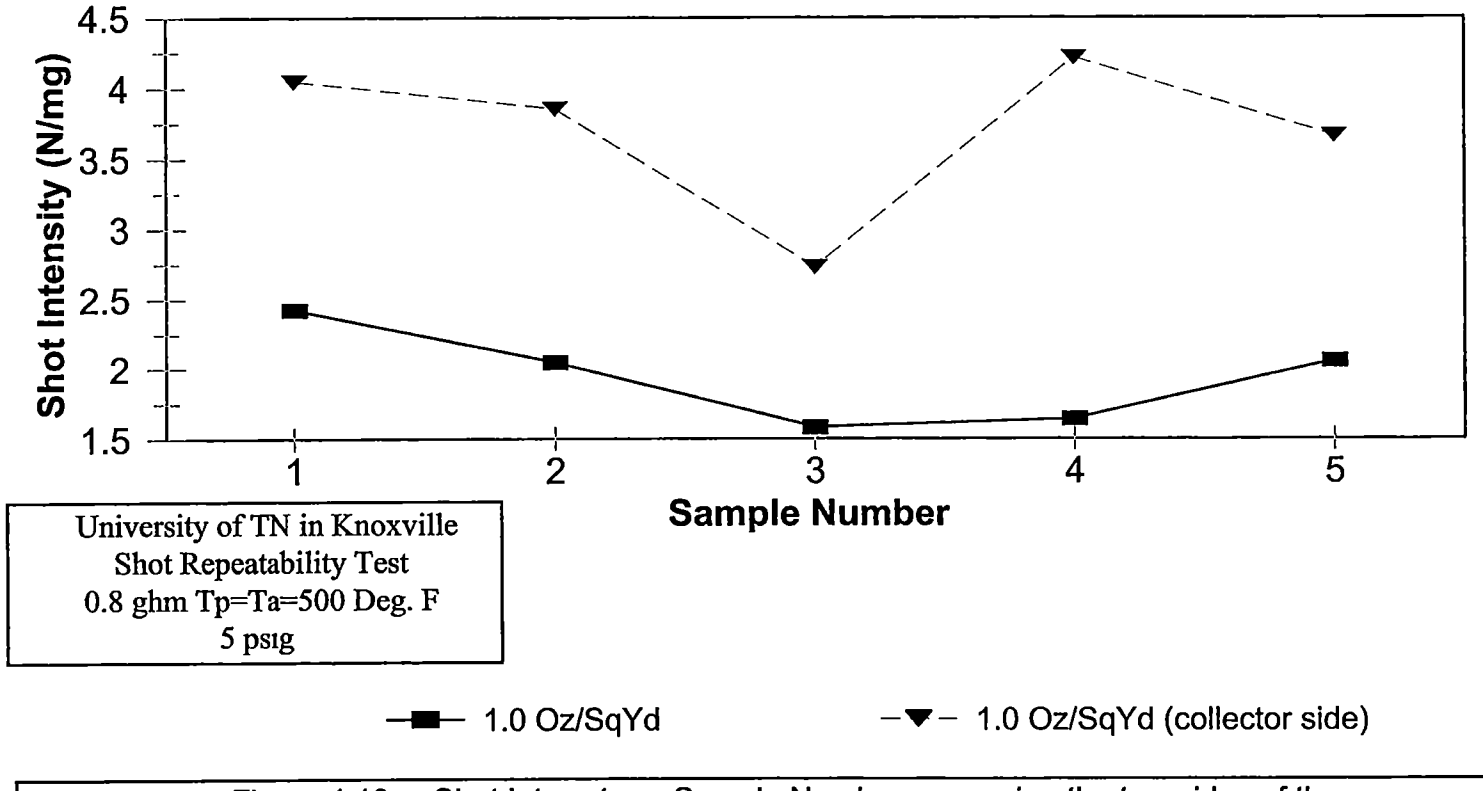


Figure 4.13 Shot Intensity vs Sample Number comparing the two sides of the web @1.0 Oz/SqYd.

unbroken fibers that do not fuse together in the air before they reach the collector The model does not address the collector itself even though it is evident that decreasing the amount of force that the fibers are exposed to when they impact the collector is something to be considered. Without the aid of high speed photography or video, it would be impossible to determine how and where most of the shot is formed. Because of this, it is necessary to do further experiments to be able to understand how shot is actually formed. The next section of this chapter provides some answers to this question by looking at samples collected from a single hole die.

Single Hole Die Experiments

This section attempts to look at what happens with a die that contains only one 0.015" orifice. One hole will not produce much material but with the collector speed turned down to its lowest possible setting before it stops completely, the single fiber was allowed enough time to build up on the collector to create a web that could be analyzed for both average diameters and shot intensity. The results found in this experimental study have shed some light on the whole issue of shot production in melt blown webs. There are several possible ways to explore the single hole die and it has been used in the past by Utsman [4], Spencer [6] and Haynes [5] for various experiments. These researchers looked at the issue of fiber diameters that were produced by the die; however, they did not find anything that

they considered as shot The results of the following show something that is certainly different from what has been seen before

The experiments performed here were intended to compare different resins and to find out how they reacted to the single hole die setup. The nosepiece is a single hole, 60° design with the throughput set at 0 8 ghm and the die setback and gap at 0.079". The air and polymer temperatures were both kept at 400°, 440°, and 480° F with four different die pressures which were 5, 8, 12, and 15 psig. Only the samples collected from the two lower pressures were analyzed since the other two were considered to be too high for the purposes of this study. The die to collector distance was also set at 16" for this group of experiments. Four different resins are presented here for comparison purposes with a range of MFR values from 700 to 1300.

The fiber diameter information found in Figure 4.14 with a psig of 8 shows nothing out of the ordinary. Figure 4.15 with a psig of 5, also contains no surprises. The average diameters are what can be expected by changing MFR and then by varying the temperature and pressure. Figures 4 16 and 4 17 contain the shot intensity information for 8 psig and 5 psig respectively These show nothing out of the ordinary until you consider that this comes from a single hole die Two things are apparent from the shot intensity data and they are that, in general, shot increases with temperature and then with pressure. As temperature increases, the amount of shot found in the web should increase. According to Utsman [4], with increasing pressure the amount of shot should decrease. This is not supported by

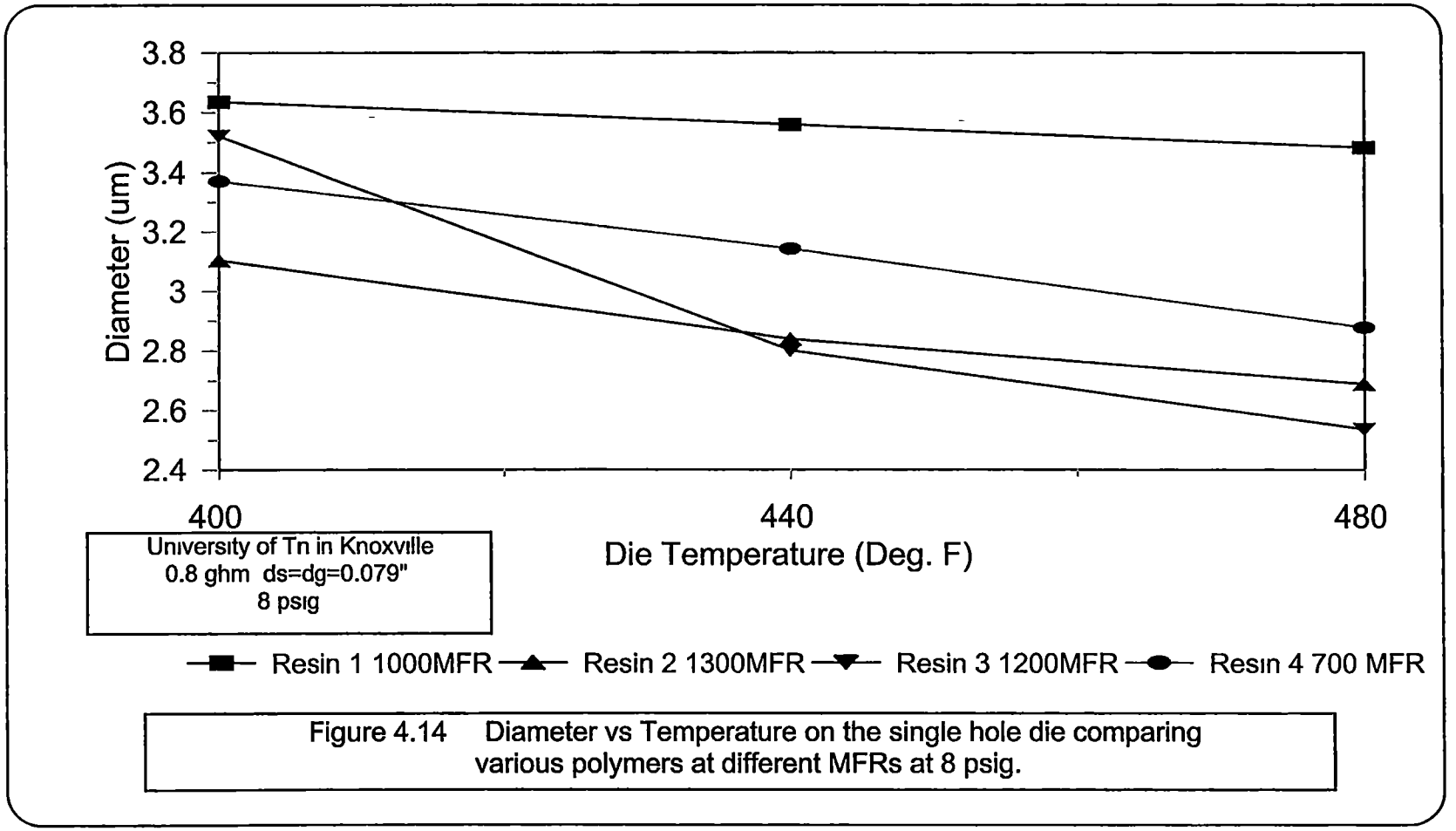


Figure 4.14 Diameter vs Temperature on the single hole die comparing various polymers at different MFRs at 8 psig.

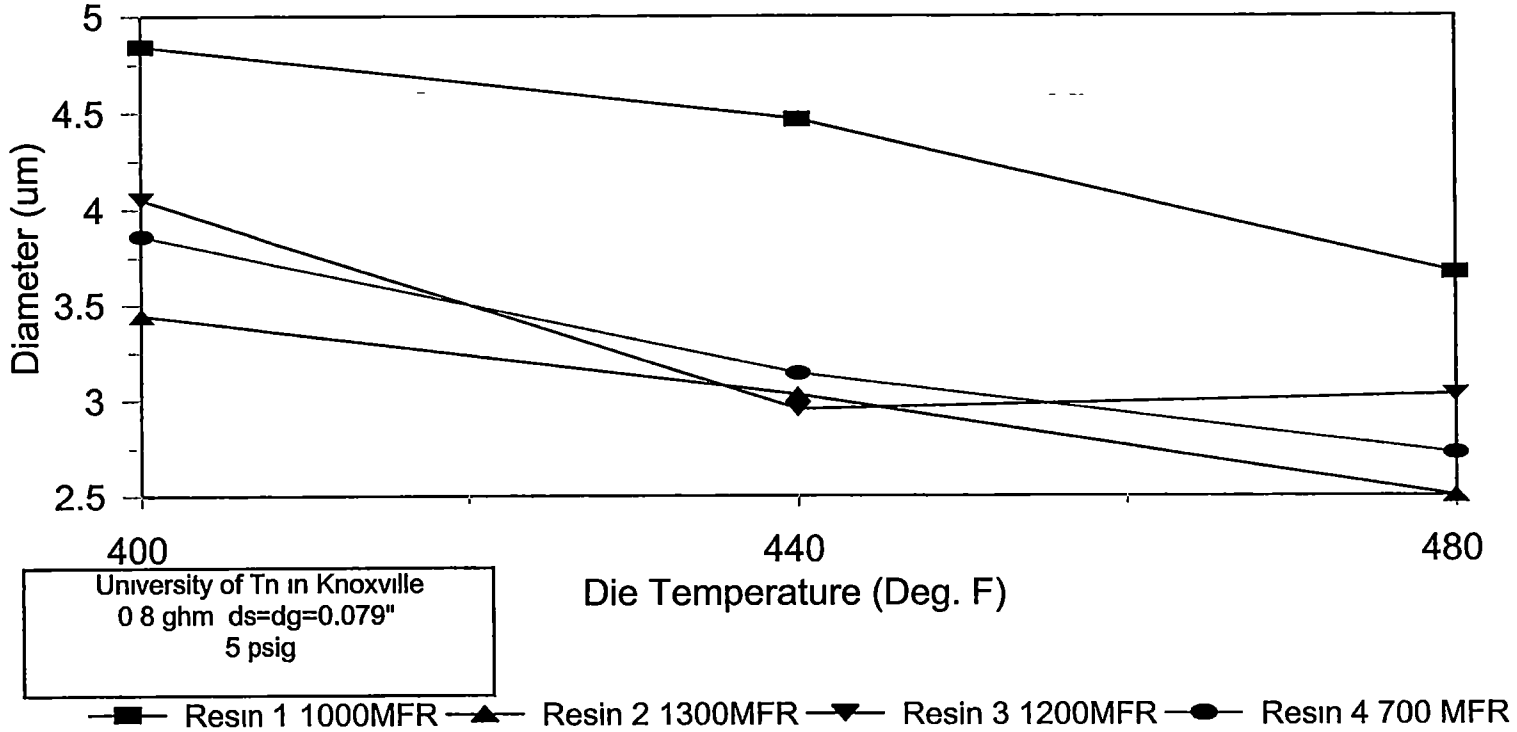


Figure 4.15 Diameter vs Temperature on the single hole die comparing various polymers at different MFRs at 5 psig.

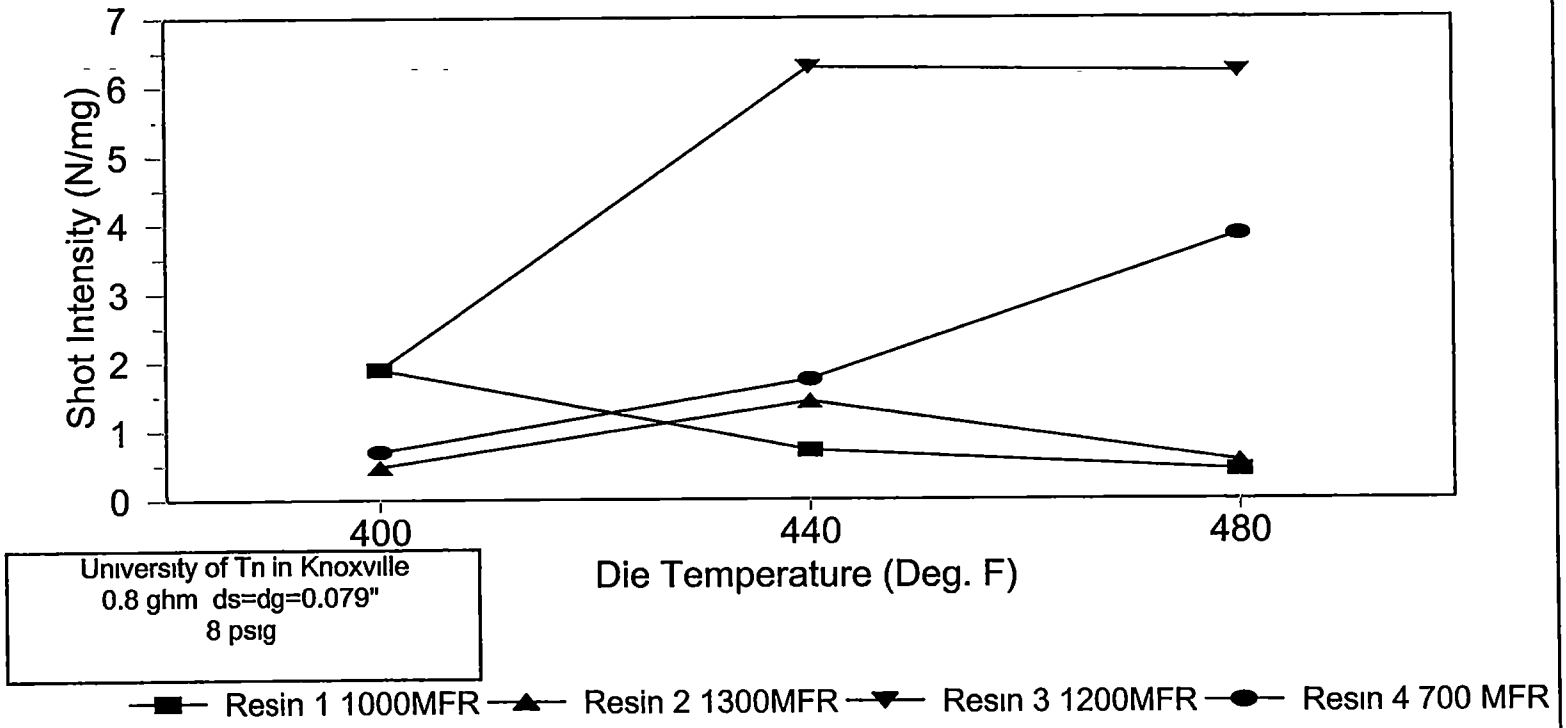


Figure 4.16 Shot Intensity vs Temperature on the single hole die comparing various polymers at different MFRs at 8 psig.

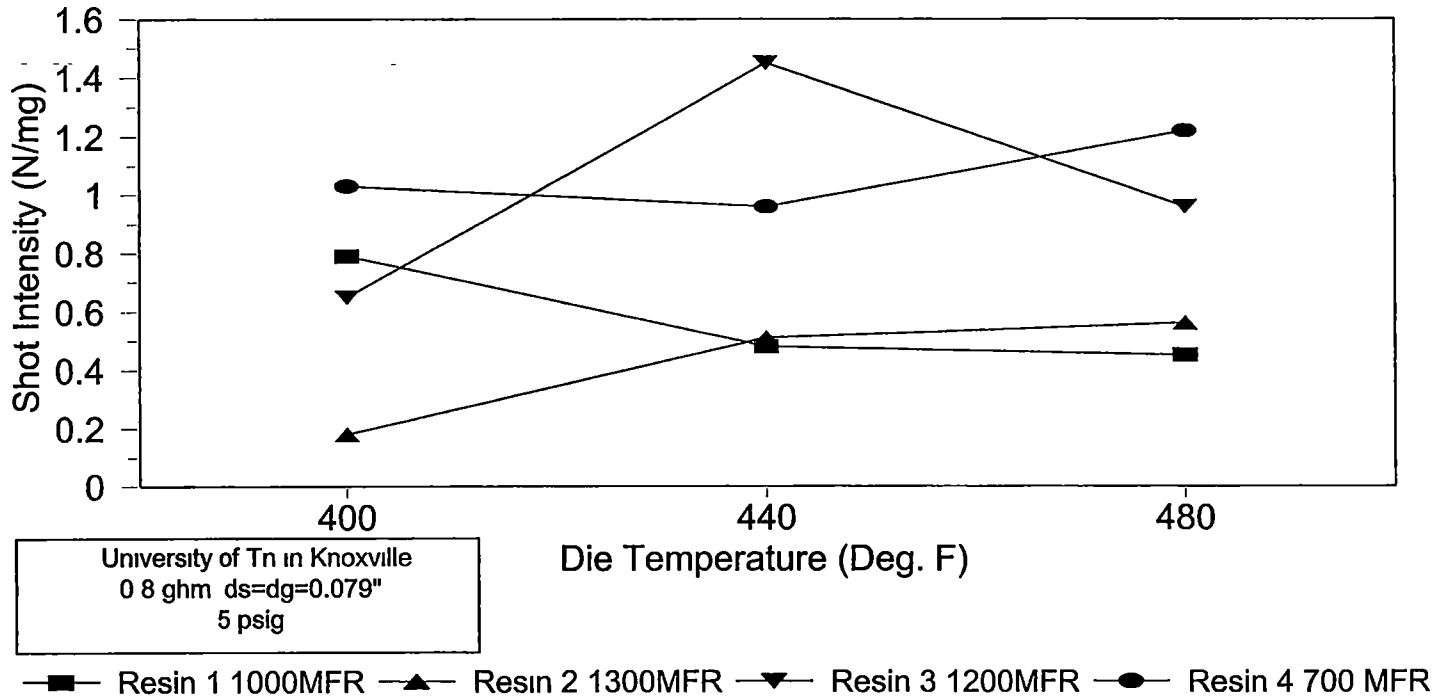


Figure 4.17 Shot Intensity vs Temperature on the single hole die comparing various polymers at different MFRs at 5 psig.

the data seen here

The question remains, however, of what is seen in the web samples that was not seen or counted as shot before Figures 4 18 and 4.19 are photographs of some of the typical globules of polymer that was seen in the web Figures 4.20 and 4.21 are examples of broken fibers that were not drawn out. The outlines of the shot are found below each photograph with its approximate size. These photographs were taken using a Nikkon microscope that was set at 40X magnification with an attached 35 mm camera specifically designed for use with the microscope. All of the shot in these photographs are from various samples collected at 5 psig and are typical of what was found in all of the samples. One last thing of importance about these images is that very few pieces of shot seen were of the type that melt the surrounding fibers to create holes in the web.

The question still remains of what happened here to create shot with a single hole die. The answer is derived from a closer look at the air pressures used in these experiments and the resulting air exit velocities With the equations determined by Spencer [6], the air exit velocities can be calculated for this experiment and in Figure 4.22 the velocities are compared for the die pressures seen in this experiment for resin 4 Even the lowest velocity seen during this experiment is rather high compared to velocities normally seen in production processes. These high velocities cause several things to happen. Higher velocities can easily break the fiber downstream and also cause an extreme fiber flapping motion to occur. Another look at the data from the extension plate study after the die air pressure is converted over to the die exit velocities, reveals the

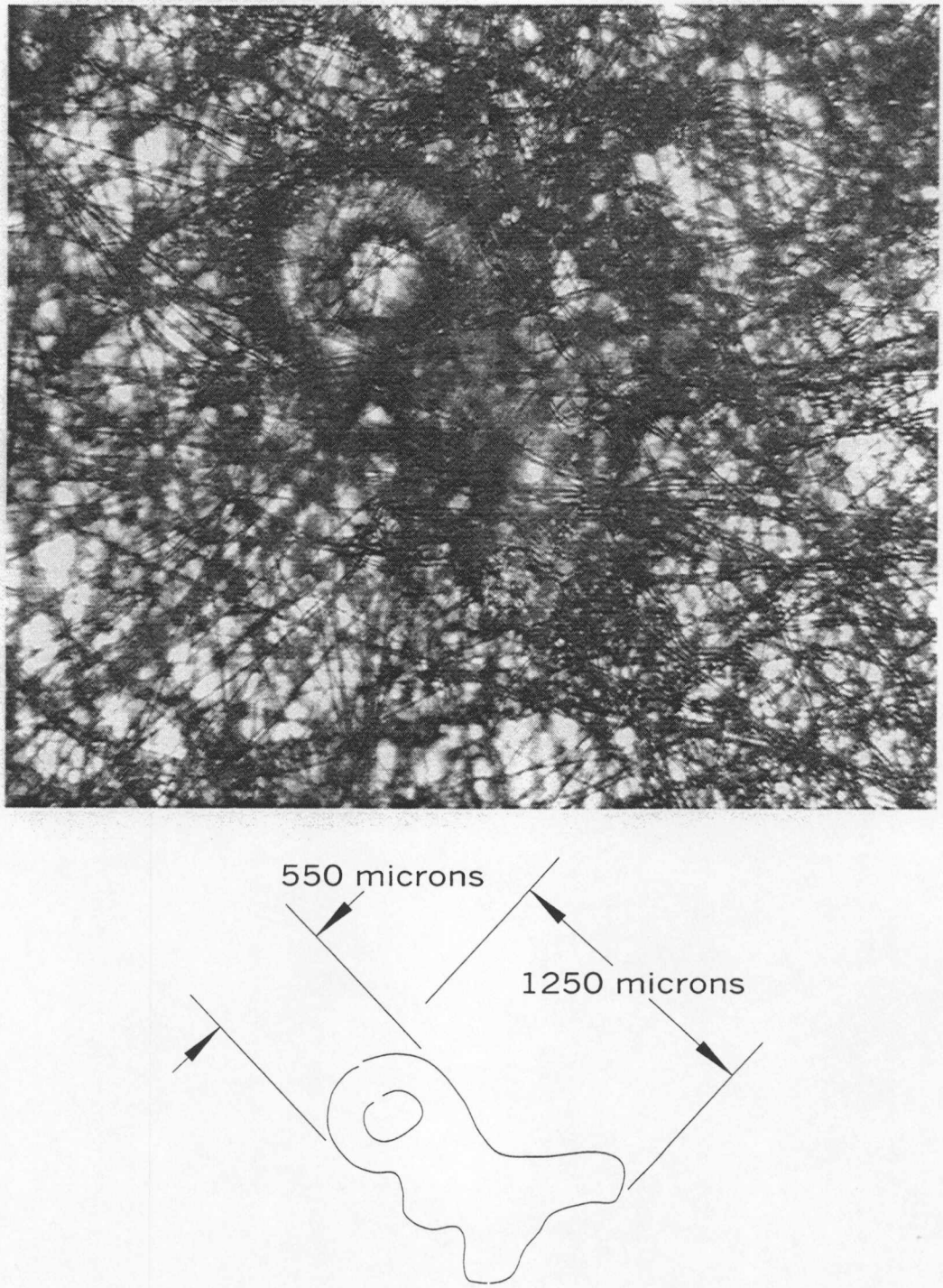


Figure 4.18 Image of shot found in a single hole die web at 5 psig and 440° F.

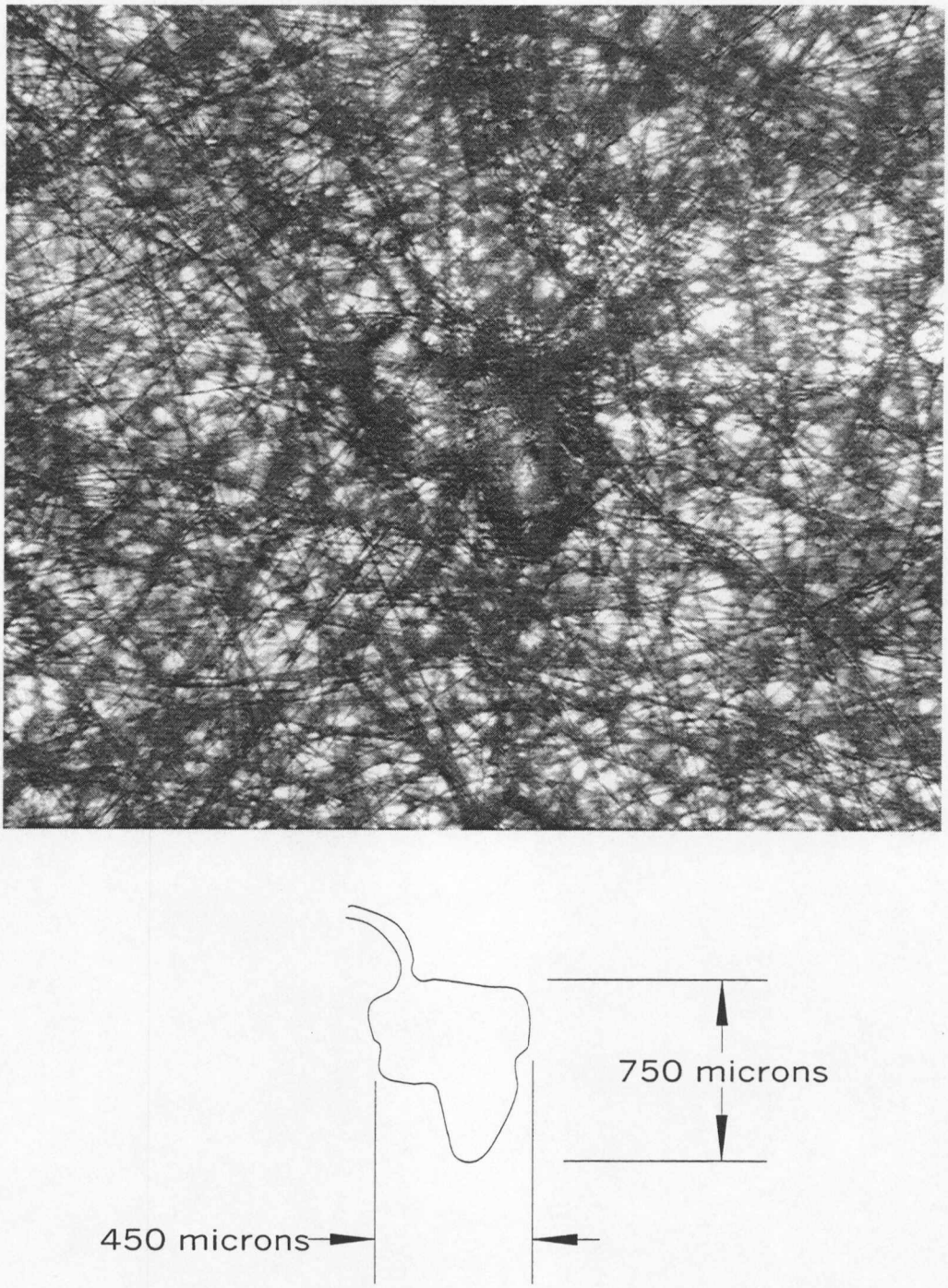


Figure 4.19 Image of second shot found in a single hole die web at 5 psig and 440° F.

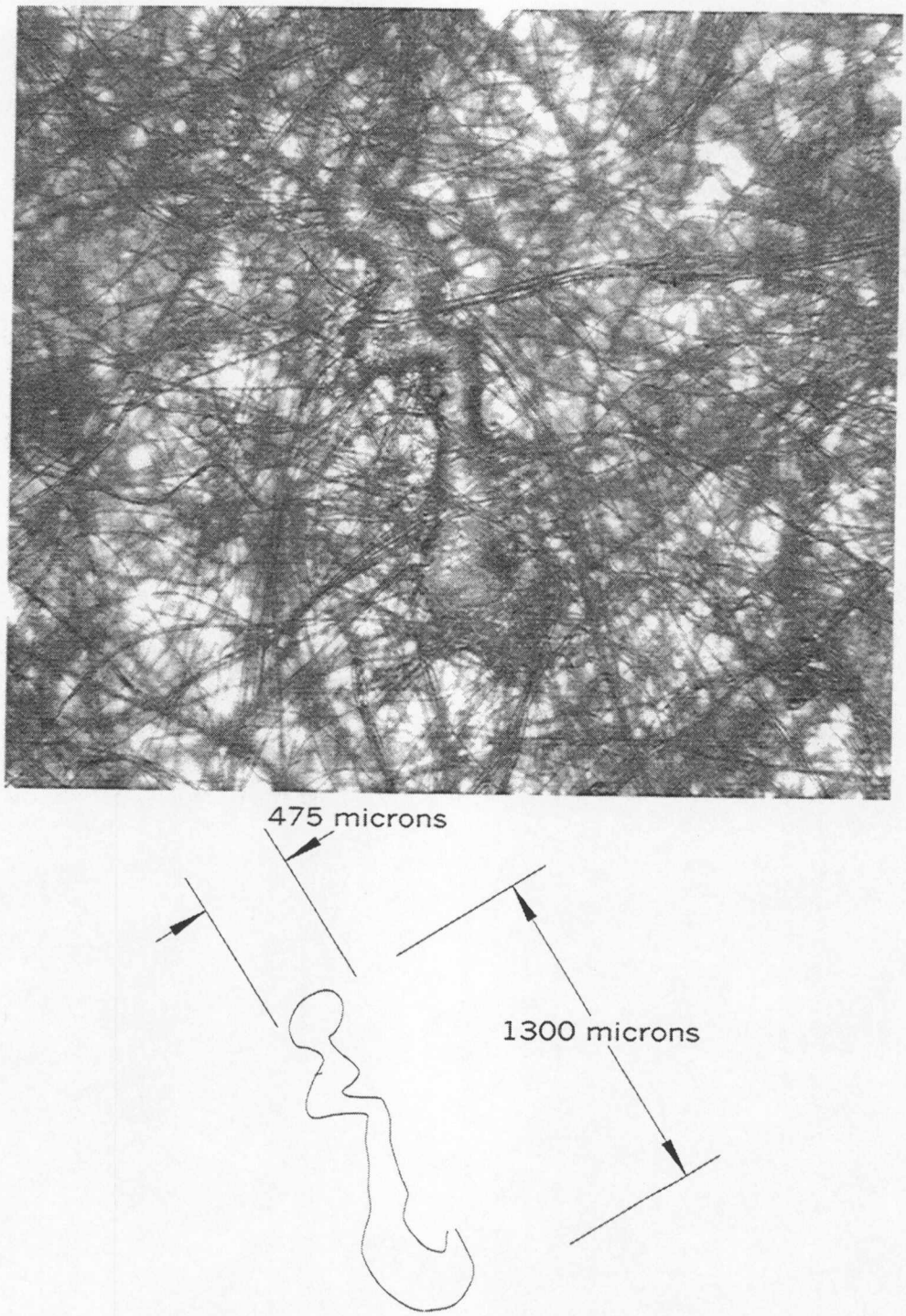


Figure 4.20 Image of shot with the appearance of a large fiber found in a single hole die web at 5 psig and 440° F.

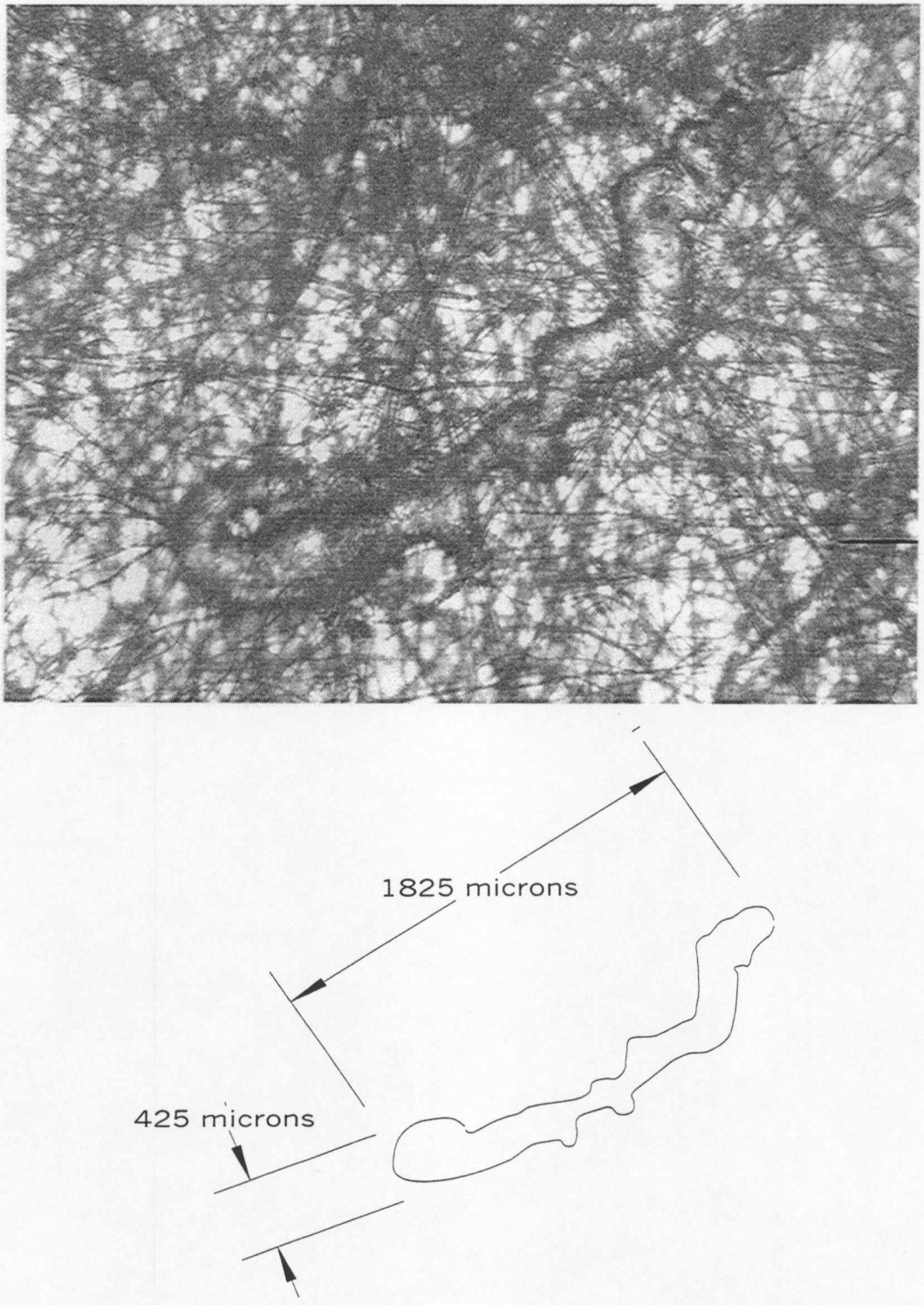


Figure 4.21 Image of second shot with the appearance of a large fiber found in a single hole die web at 5 psig and 440° F.

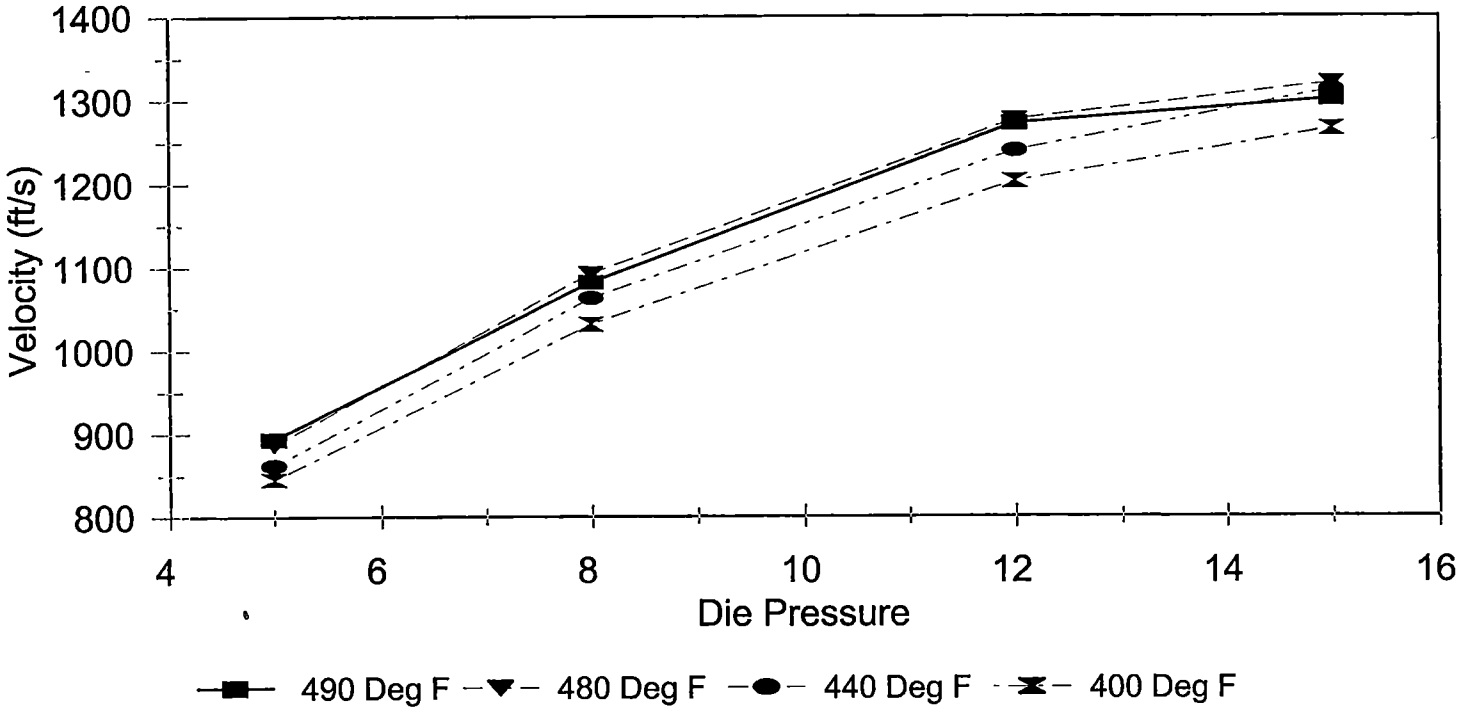


Figure 4.22 Die Exit Velocity vs Die Pressure for various air temperatures for resin 4.

same thing. Figure 4.23 indicates that there is a point at which the amount of shot created in the web begins to increase dramatically When the air velocity reaches this point and goes beyond, fly becomes very apparent in the air surrounding the collector The highest velocities reported by Utsman [4] were in the range of 300 to 330 m/s or about 980 to 1080 ft/s It is only after 1100 ft/s that the amount of shot begins to increase. Although there could be other possible explanations for this increase in shot at such high velocities, this leads to the conclusion that the increase in shot comes from the broken fibers created by high air velocities. It is also apparent from the Figures 4.20 and 4.21 that fibers are broken somewhere between the die and collector and sometimes form pieces of shot. When a fiber breaks, it can easily wrap itself up to create the necessary mass of polymer that forms shot. The next three figures are from a high speed video camera that was recently purchased by the EXXON Corporation specifically for filming the melt blown process The images are from a closeup of approximately 0 5" wide by 1" long looking at a single hole nosepiece from underneath. Figure 4 24 shows the typical fiber being drawn out with Figures 4.25 and 4.26 demonstrating some of the extreme motion of the fiber. With the images seen here, it is evident that an individual fiber can be wrapped up even on itself

Another important piece of information to consider is how a single hole web compares to a web produced by the standard multi-hole die The fiber diameters are not much different. This is evident by looking back at figures 4.3 and 4.15. From Figure 4.3, the 700 MFR resin produces a web at an air temperature of 440° F and a polymer temperature of 450° F that has a mean diameter of 3.25 microns.

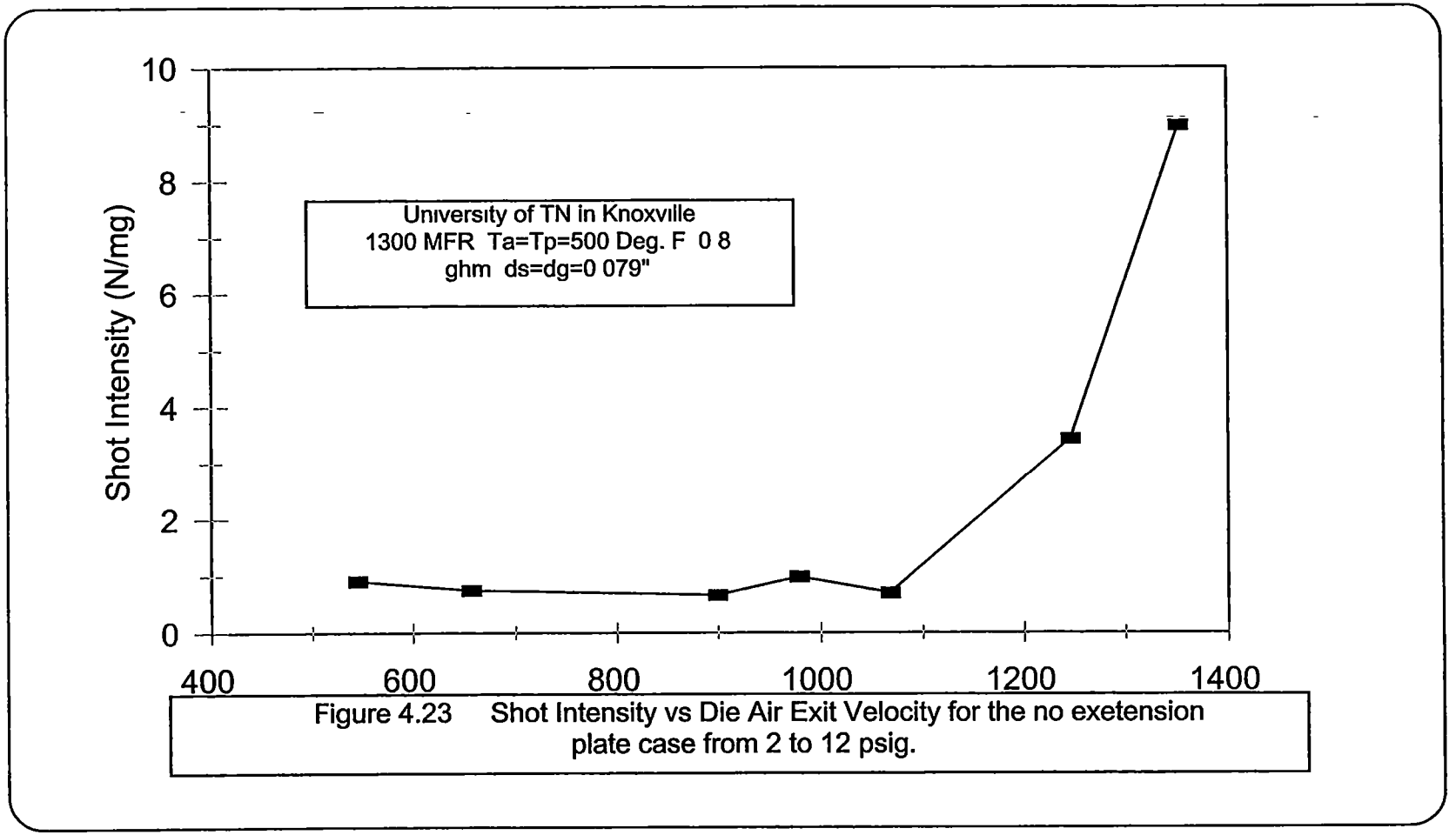


Figure 4.23 Shot Intensity vs Die Air Exit Velocity for the no exetension plate case from 2 to 12 psig.

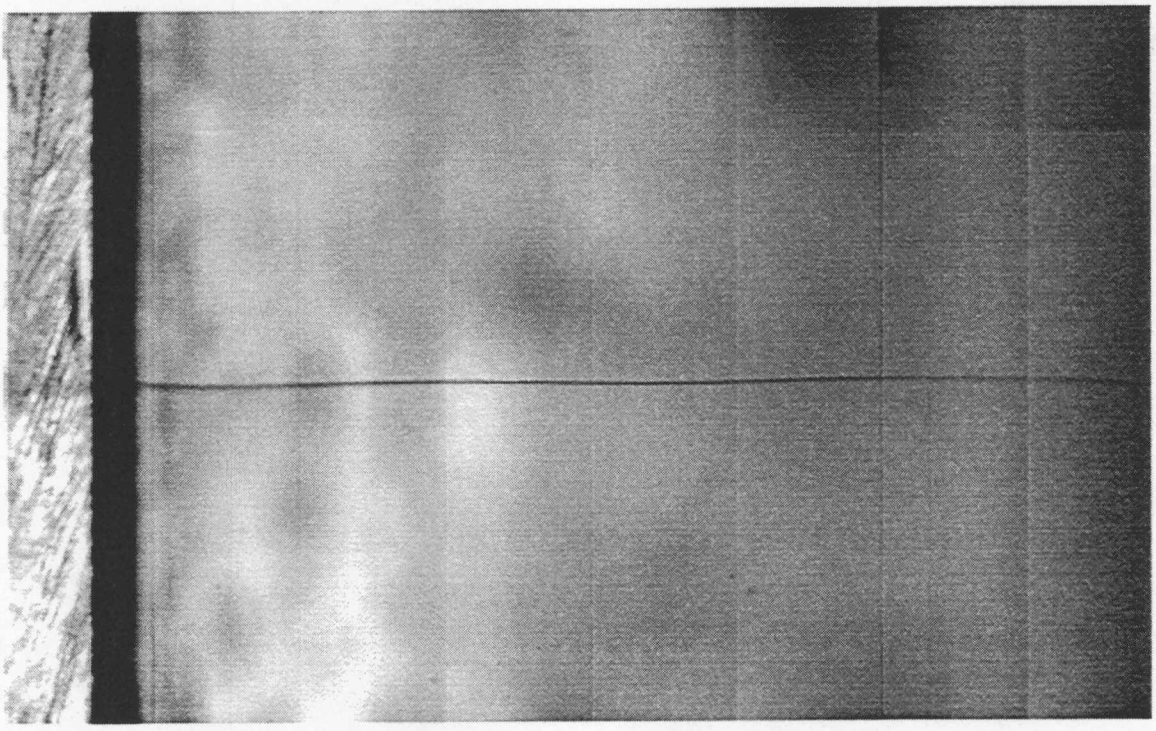


Figure 4.24 Image taken using a high speed video camera from a single hole die.

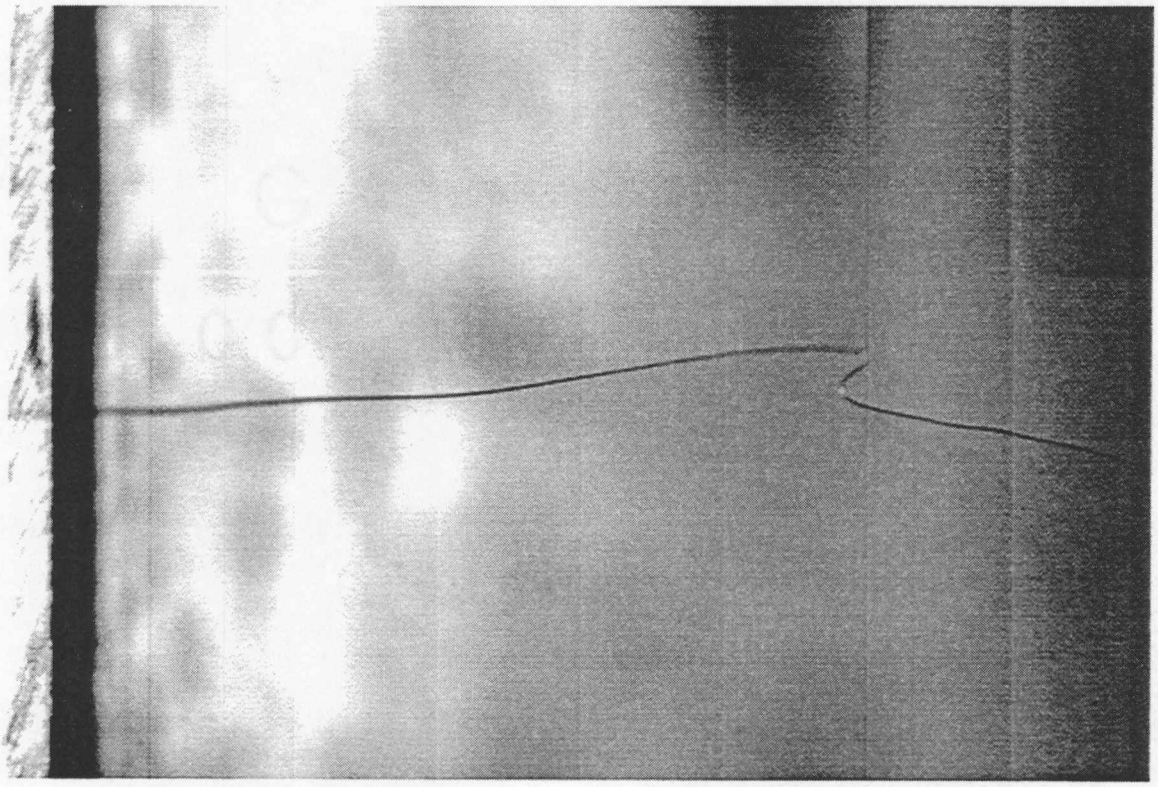


Figure 4.25 Second image taken using a high speed video camera from a single hole die.

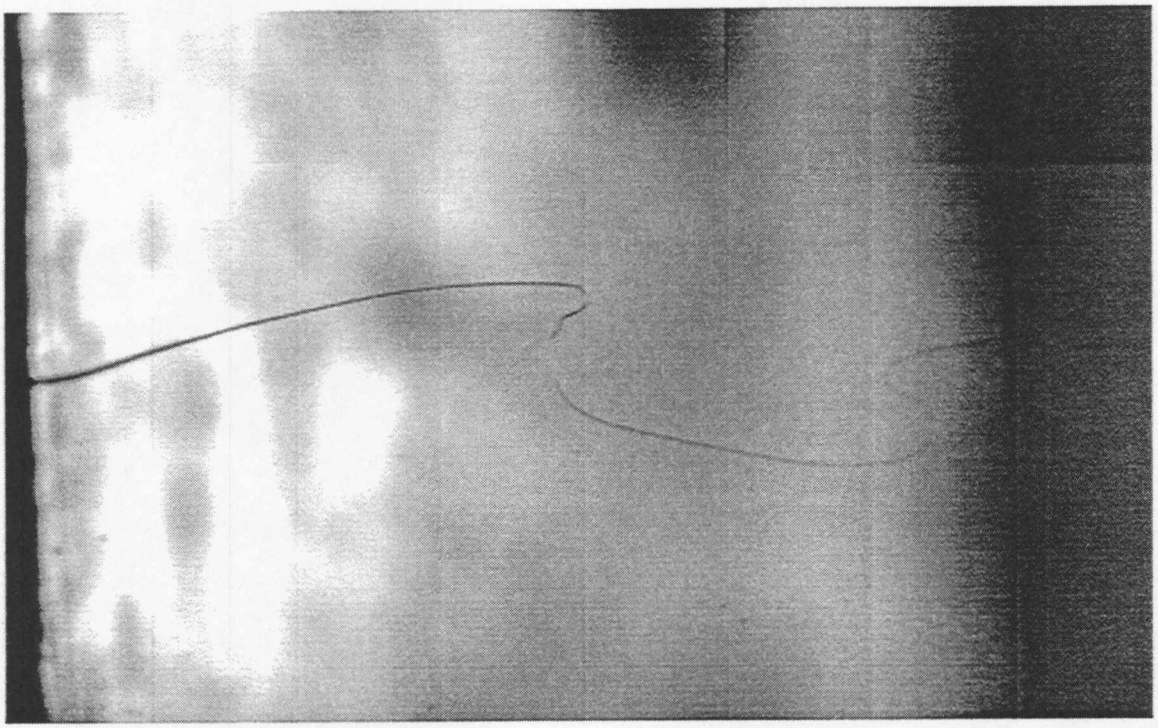


Figure 4.26 Third image taken using a high speed video camera of a single hole die.

The single hole die information in Figure 4.15 shows that a web produced with the same resin at 440° F die and air temperatures also has a mean diameter of 3.25 microns. This is not surprising considering that diameters should not depend on the number of holes in the nosepiece

Shot information is different because of the interaction of the fibers in a multi-hole die design. Figure 4 27 is shown here with the shot intensity information from figure 4.15 compared to previous information from a web produced by a 30 hole die. The 1300 MFR resin is chosen for this comparison since more information was collected on the 30 hole die with it than with the 700 MFR resin. More shot is produced by the 30 hole die. This can only make sense when one considers that the fibers do not come straight out of the die as shown in the Figures 4.24 thru 4.26 If there were any fibers in close proximity to one that was flapping around, then that fiber would obviously come in contact with another one sooner or later. Once two or more fibers touch and fuse together, then it would only make sense that the new and larger fiber would reach the web as a piece of shot. This is evident in the fact that each fiber must be partially solidified before it reaches the collector or else it will form shot If the fiber becomes too large, then it will not have enough time to solidify The extra fibers in close proximity and their interaction explain the differences between the two sets of data

What has been found in this series of tests indicates that fibers can break and cause the defect known as shot This is evident in several ways by looking at the accompanying figures and images With this knowledge, and by understanding that individual fibers need a certain amount of time for quenching

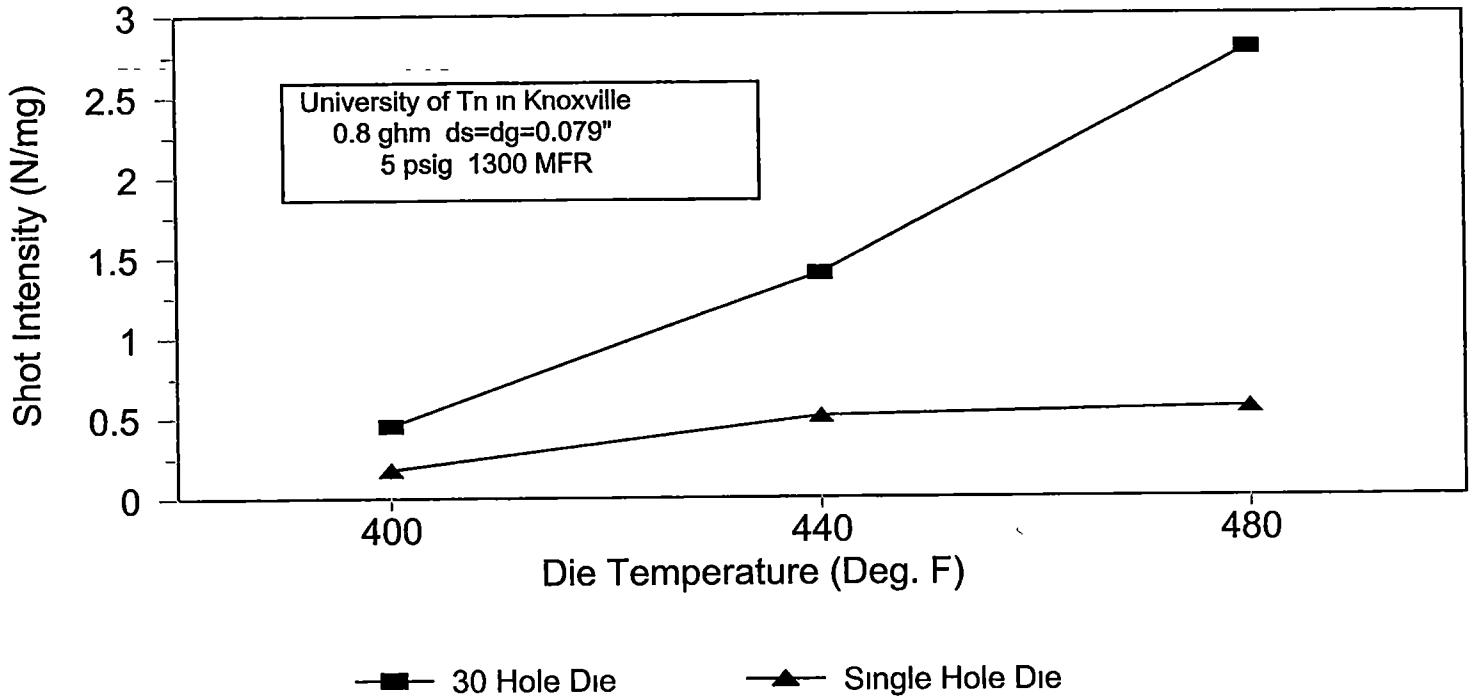


Figure 4.27 Shot Intensity vs Temperature comparing the single hole die to the 30 Hole Die at 5 psig with three different temperatures.

before it reaches the collector, it is possible to reduce the formation of shot. There are then two ways that shot can be formed between the die and the collector that were discovered in this study. In both cases, the fibers must somehow become too large to be properly quenched before they reach the collector. One possible way is for a fiber to become too large by touching and fusing with itself or with another fiber This can happen through the erratic motion of individual fibers in the air The other way that shot can be formed, is when the fiber breaks and is not drawn out properly as it approaches the collector. This could mean that the fiber exhibits the "snap back" characteristics that reseachers in the past have believed to exist with these fibers. Since it is now possible to film the process using high speed video, it should become clear within a few years where shot is formed in the airstream Understanding this will aid those in the melt blown industry in making appropriate process changes to reduce shot formation in material they produce.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

There were several key ideas presented here on the fiber melt blowing process that will help improve the production of non-woven material. The processes involved in creating fine fibers with minimal shot are complex since a small change in any one parameter can have an impact on the final material. The following conclusions can be drawn from the findings presented in this thesis.

1 Both Webpro and visual inspection under a microscope have been shown to produce acceptable results for comparing fiber melt blowing webs.

2. Although several extension plates were experimented with in an attempt to control the airstream as it exits the die, the results show that all of the revisions adversely influence both fiber diameter and the amount of shot produced in the web As the plates were moved closer to the centerline of the die, the fiber diameters and shot intensity were shown to increase.

3. The slit die design was shown to be ineffective at producing melt blown material due to the large amount of shot found in

the collected samples.

4. The angled hole die produced fiber diameters that are very close to those produced by the standard design The angled hole design produced mixed results with much larger amounts of shot seen when the die setback was changed from 0 079" to 0.0" Less shot, however, was produced with the angled hole design than the standard design at a throughput of 0.4 ghm.

5 These experiments demonstrate that excessively high air pressures (higher than that normally seen in the industry) cause the die air exit velocities to reach high enough levels to cause the fibers to break and create fly

6. Shot can also be controlled by decreasing air and resin temperatures but with the disadvantage of increasing fiber diameters

7 Increasing throughput and the rotational speed of the collector decreased shot intensity of the web material up to a certain point

8 Resin material is another important factor in controlling shot production in melt blown webs with MFR as one the most important characteristics of the resin It was shown that by increasing MFR substantially, shot was reduced by at least 50% for the two resins that were compared here

9. The die to collector distance was shown to have a major impact on melt blown webs Fiber diameters increased as the collector was moved further away from the die but the amount of shot was reduced As the collector was moved closer to the die, the fiber diameters were decreased with an increase in shot Shot was never completely eliminated from the web by moving the collector back, but it was reduced by as much as a factor of 8

10. A soft or padded surface reduced the amount of shot seen in a web compared to the typical fine wire screen mesh used for most collectors. This indicates that the amount of force that the fibers experience when they hit the collector influence the amount of shot produced. The larger the force, the more shot is seen in the final web material.

11 The single hole die design was found to produce shot with an increasing amount as the die air pressure is increased. This is caused by the fiber breaking and also when the fiber wraps itself up before it reaches the collector

RECOMMENDATIONS

From the previous conclusions, the following ideas are recommended for further experimental and analytical work on the melt blown process.

1 The extension plates have demonstrated that there is a relationship between the die exit airstream, and final diameters and shot found in the web material. Further experimental work could determine this relationship which would help in producing better die designs. Experiments such as using high speed video to film the process close to the die as the plates are moved closer to the centerline of the die would show the effect the plates have on fiber motion

2 The angled hole die design should also be further investigated to determine if it is a feasible design that could help reduce shot formation in the final material Several experiments can be conducted by using high speed photography or video by looking at fiber motion from the side of the die. Also, experiments with changing throughputs and die setback would provide further information on how these two parameters influence material produced by this new design.

3 Since the relationship between throughput, fiber diameters and shot could not be determined here, another experiment with

this parameter could provide more accurate information. One possible way to approach this is to look at a smaller range of throughputs and keep the collector speed constant.

4. Single hole shot formation is something that was never noticed before and should be further explored to determine for certain if it is caused by the high air exit velocities in these experiments or if it is a result of something else. Several experiments should be done with changing the die air pressure from at most 2 psig to at least 8 psig which will extend the range of the experiments presented in this thesis. Also, the samples could be collected at different distances from the die to determine if and where the fiber is breaking under various conditions.

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VITA

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John is currently working in the oil industry as a Product Design Engineer at Cooper Cameron in the Cameron division