DESIGN EQUATION FOR THE LIP OPENING OF A FILM EXTRUSION DIE

A Thesis

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By

Andrea C Jones, B.S.

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The Ohio State University

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Dissertation Committee:

Professor Jose M. Castro, Advisor

Professor Allen Y. Yi

Approved by

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Advisor
Industrial and Systems Engineering
Graduate Program

ABSTRACT

This research is focused on modeling the manufacturing process for DuPont Teflon® Film. In particular, the design of the manufacturing die with respect to the die lip opening is most important. Therefore, the equation for the die lip opening of an end-fed plastic extrusion die was derived, using Newtonian fluid and Power-Law fluid assumptions. This equation was compared to the lip opening of an actual manufacturing die used for commercial production of DuPont Teflon® Film. The theoretical results were consistent to the actual lip opening range.

To extend the usefulness of this equation, it was derived using two approaches, one that includes pressure and flow rate terms and one that only includes geometric and material parameters. The first is useful for process design while the later is useful for setting the die lip opening. The later version of the equation illustrated the relationship between the minimum die lip opening and the maximum die lip opening which is only dependent on geometric parameters and the power law index.

As an example of the use of the equation, the maximum lip opening versus the minimum lip opening was plotted for varying power law indexes. From this chart, the die lip opening can be quickly determined.

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VITA

September 16, 1975……………..Born – Chicago, IL

1998………………………...........B.S. Mathematics, Spelman College, Atlanta GA

1998…………………………………B.S. Mechanical Engineering, Georgia Institute of Technology, Atlanta GA

2001-2003………………………..Process Engineering, DuPont Fluoroproducts, Circleville, OH

PUBLICATIONS

None

FIELD OF STUDY

Major Field: Industrial and Systems Engineering

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Hmax: Maximum opening in the lips of the die

Hmin: Minimum opening in the lips of the die

n: power law index

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

DuPont is a leader in the production of fluoropolymer resins. Teflon® is a registered trademark of DuPont and is used in relation to products manufactured with DuPont's fluoropolymer resins.

DuPont™ Teflon® FEP film is a transparent, thermoplastic film that can be heat sealed, thermoformed, vacuum formed, heat bonded, welded, metalized, laminated-combined with dozens of other materials, and can also be used as an excellent hot-melt adhesive. This film is used in various applications such as chemical tank liners, food belt covers, blood bags, rupture disk liners, electrical circuit boards, etc. The wide variety of fabrication possibilities augmented with inert properties, offer a unique balance of capabilities not available in any other plastic film [2,4].

DuPont makes available a wide choice of dimensions for industrial use, as shown in Table 1.1. Three dies are used to make the array of film thicknesses. A 60” die is used to produce film 60mil and thicker. A 67” die is used to produce film between 10mil and 20mil. A 78” die is used to produce film .5mil to 10mil thick.

Gauge	**50**	**100**	**200**	**300**	**500**	**750**	**1000**	**1500**	**2000**	**3000**	**6000**	**9000**	**12500**	**19000**
Thickness, mil	0.5	1	2	3	5	7.5	10	15	20	30	60	90	125	190
Thickness, µm	12.5	25	50	75	125	190	250	375	500	750	1500	2300	3125	4750
Approximate area factor, ft^2/lb	180	90	45	30	18	12	9	6.0	4.5	3	1.5	1	0.72	0.47
Approximate area factor, m^2/kg	36	18	9	6	4	2.5	2	1.2	1	0.6	0.3	0.2	0.14	0.09
Availability														
Type A—FEP, general-purpose	X	X	X	X	X	X	X	—	X	—	—	—	—	—
Type C—FEP, one side cementable	X	X	X	X	X	—	—	—	—	—	—	—	—	—
Type C-20—FEP, both sides cementable	X	X	X	—	X	—	—	—	—	—	—	—	—	—
Type L—FEP, high stress crack resistance in extreme environments	—	—	—	—	X	—	X	X	X	X	X	X	X	X

Note: Each roll of DuPont film is clearly identified as to resin type, film thickness, and film type.

FEP 500 C

Resin type

Film thickness, 500 gauge, 5 mil

Film type cementable one side

Table 1.1: Types and Gauges of DuPont FEP Fluorocarbon Film

One of the concerns of the customer and a challenge for DuPont is to provide film with uniform thickness and no defects. Achieving uniform thickness is highly dependent on the design of the die.

1.2 MATERIALS

Fluoropolymers

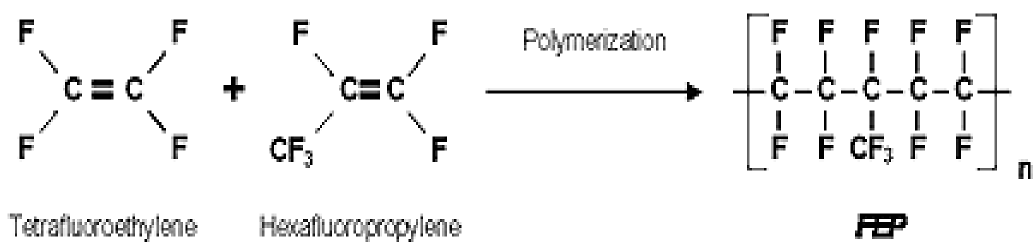
The chemical structure of fluoropolymers (also called fluoroplastics) primarily consists of carbon and fluorine. The particular combination of these two chemical elements arranged along the molecular chain imparts a unique set of properties to these types of carbon - fluorine based polymers.

Fluoropolymers are among the most chemically inert of all polymers and remain stable in almost all chemical environments. These high performance properties are a direct result of the unique chemical structure of fluoropolymers, which differs significantly from the structure of traditional polymers such as polyethylene.

Understanding the chemical structure gives a better understanding of why the fluoropolymers have such outstanding chemical resistance (and other properties).

Fluorinated Ethylene Propylene (FEP)

FEP is a copolymer of tetrafluoroethylene and hexafluoropropylene of the form [3]:



FEP has a low coefficient of friction, excellent insulating properties, and is chemically inert to most substances. It also can withstand high heat applications and it is well know for its anti-stick properties. FEP is highly resistant to stress-cracks and has a maximum recommended use temperature of nearly 400 degrees F (204 degrees C) [1].

1.3 DIE FORMING PROCESS

Dies are metal flow channels or restrictions that serve the purpose of imparting a specific cross-sectional shape to a stream of polymer melt that flows through them [6]. Dies are primarily used in extrusion processes to continuously form products such as profiles, tubes, films, sheets, and fibers. A schematic of a typical film processing die is shown in Figure 1.1.

The die used to produce Teflon® film, shown in Figures 1.2 to 1.4, is an end fed die and is composed of the following elements:

- Manifold: evenly distributes the melt to the land region.
- Land: streamlines melt into final opening
- Die lips: designed to give proper cross-sectional shape of product and allow melt to forget non-uniform flow experience

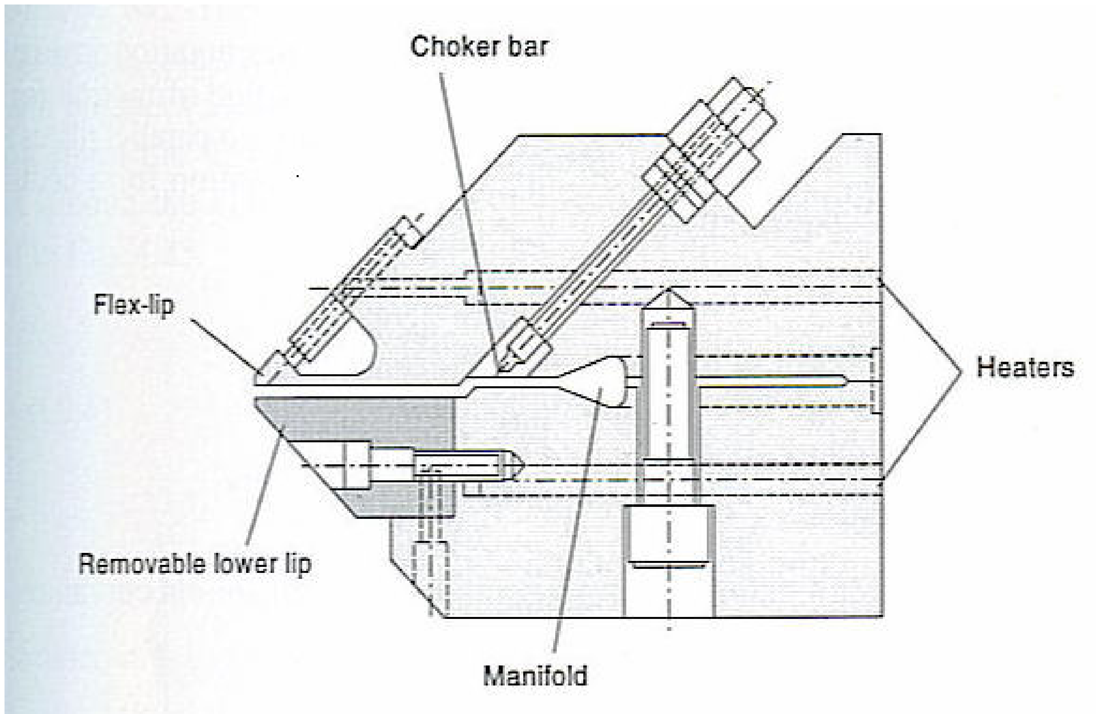


Figure 1.1: Schematic cross-section of typical film processing die

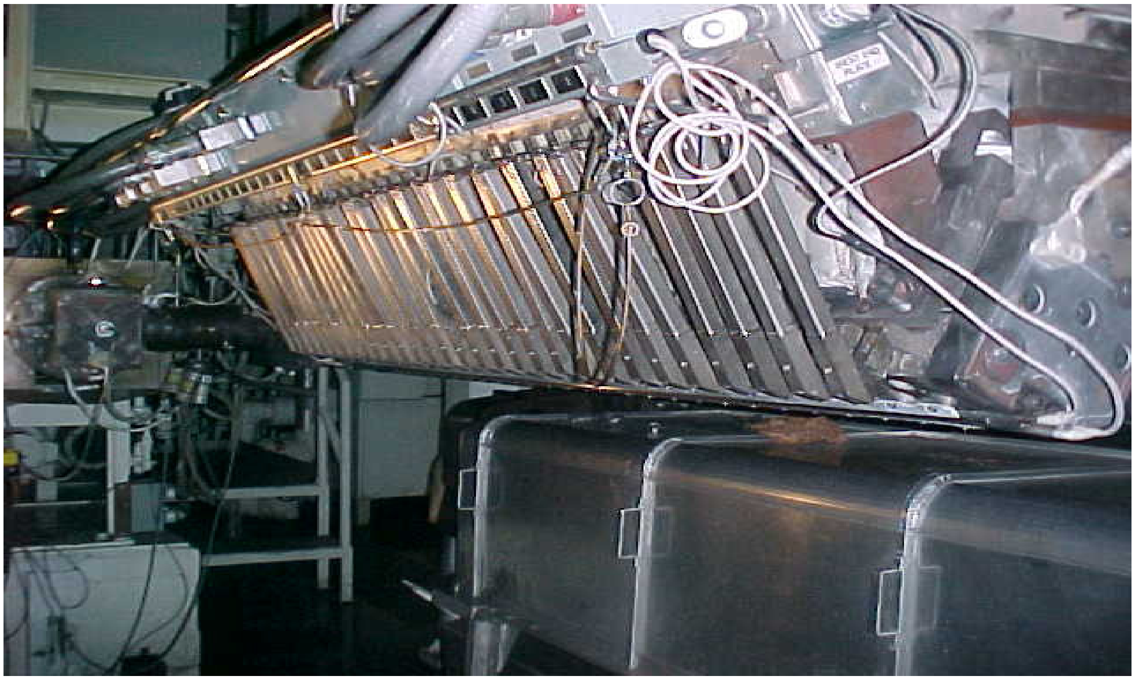


Figure 1.2: Assembled Die Machine used for film manufacturing at DuPont-Circleville, OH

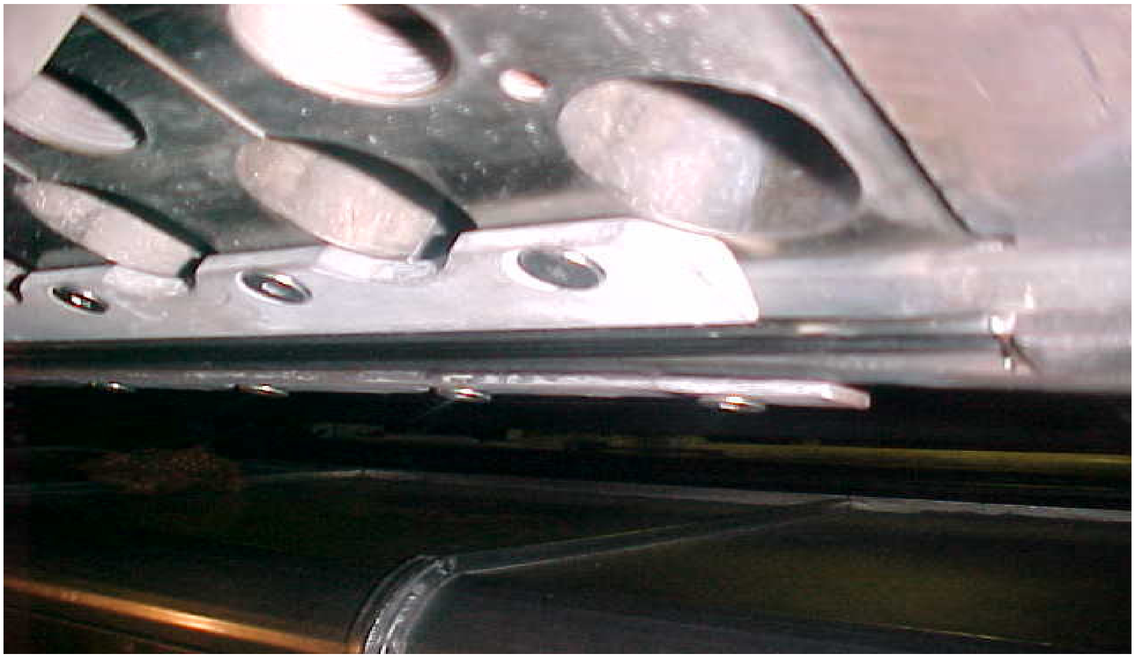


Figure 1.3 Lips on the die of the film manufacturing die used at DuPont – Circleville, OH

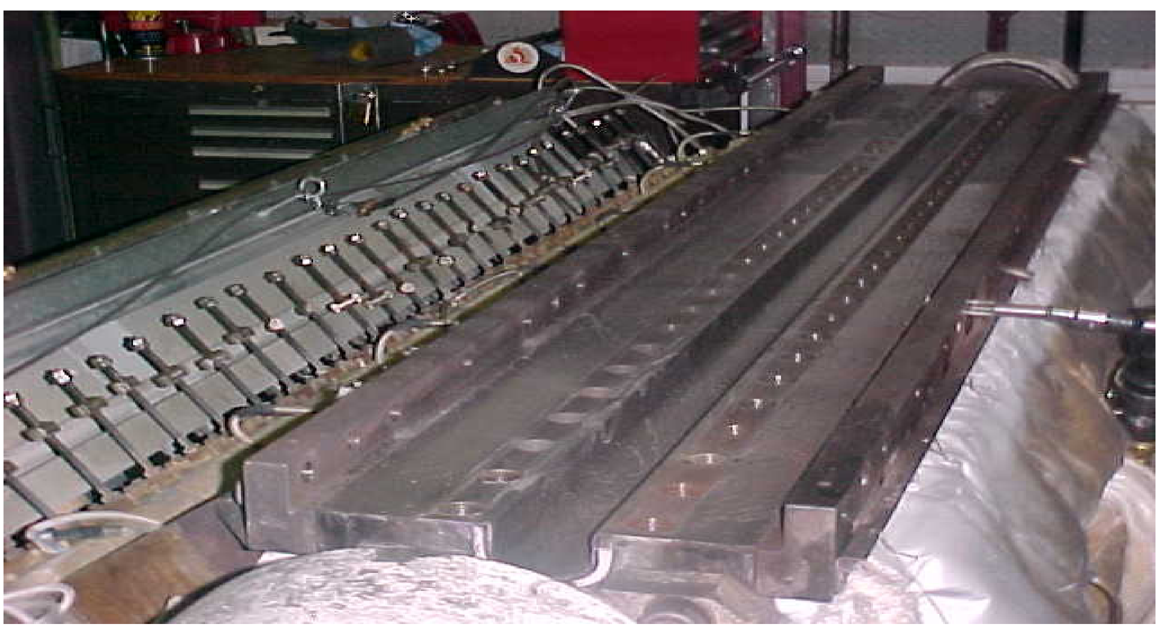


Figure 1.4: Die manifold of film manufacturing die used at DuPont – Circleville, OH

1.4 DIE DESIGN GOALS

The goal of the die design is to distribute the melt and deliver it to the die lips so that a uniform flow rate out of the die is obtained. To accomplish this, the shape of the manifold and approach channel (Land) must vary in the cross-die direction, see for example Figures 1.5 and 1.6. The dies used in actual manufacturing, usually have the ability to make fine adjustments to correct for temperature gradients, bending, and other factors.

The engineering objectives of a die design are achieving the desired shape within limits of dimensional uniformity and doing this at the highest possible production rates. Intrinsic upper limit in throughput are set by the phenomenon of melt fracture of the polymer

To generate a uniform extrudate at the die lips, the geometry at the manifold must be specified appropriately [6, 7].

The machine direction of the die is the main direction of polymer flow. In this direction, non-uniformities originate from time variation in the inlet stream (volumetric flow rate-Q, temperature - T, pressure - P).

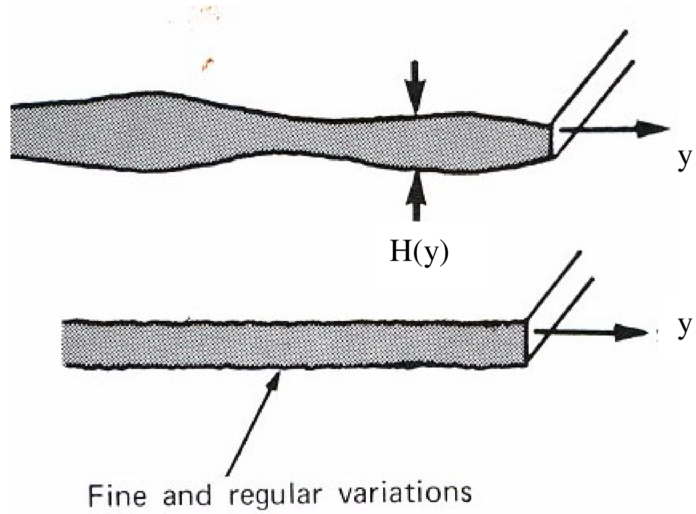


Figure 1.5: Extruded film profile

The cross machine direction (direction perpendicular to the machine direction) will also have sources of non-uniformity. These sources are most often improper die design, temperature non-uniformity, deflection due to pressure, periodic instabilities in downstream equipment.

1.5 OBJECTIVE

The objective of this work is to determine an equation for the die lip opening (h(z)) so that the flow rate out of the die is constant in the cross machine direction in order for the film thickness to be uniform. This will be done for Newtonian fluid and Power Law fluid, using standard equations for slit flow and pipe flow. The problem's generic geometry is shown in Figure 1.6 below.

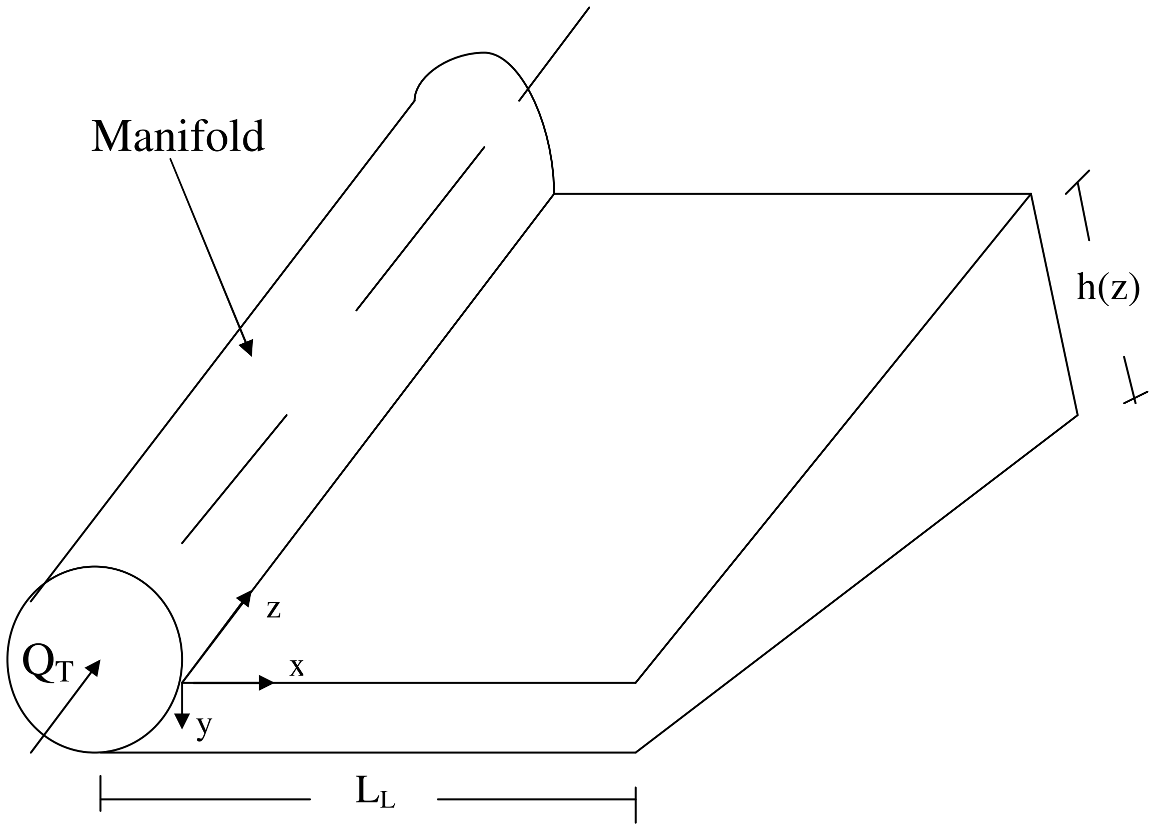


Figure 1.6: Geometric representation of the die with coordinates and variables identified.

The die geometry is divided into two sections, as shown in Figures 1.7 and 1.8 below:

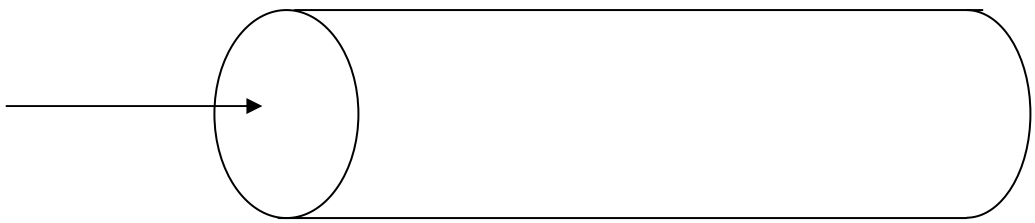


Figure 1.7: Geometric representation of the die manifold

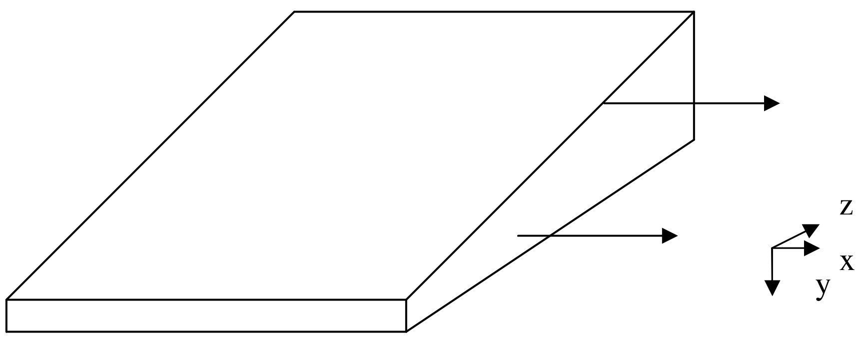


Figure 1.8: Geometric representation of the die land

ASSUMPTIONS:

General

- Newtonian fluid with constant density and viscosity (Part 1)
- Power Law fluid (Part 2)
- Isothermal
- Steady State

The methodology to be followed is:

1. Assuming Newtonian Flow, use analytical solutions for flow between parallel plates and tubular flow, then based on known parameters, determine equation for lip opening.

2. Assume Power law flow and use appropriate analytical solutions to determine the equation for the die lip opening. Compare results to actual manufacturing parameters.

3. Develop practical uses of the equation to aid manufacturing processes reduce machine downtime.

CHAPTER 2

DIE DESIGN FOR A NEWTONIAN FLUID

For simplicity, we first derive the die lip equation for a Newtonian fluid. The die manifold will be represented by pipe flow and the die lips will be represented by parallel plates (slit flow).

2.1 PRESSURE AND FLOW RATE EQUATIONS

For clarity, we first develop the equation for the die lip opening (h(z)); using the flow rate and pressure drop equations. Thus, the equation first derived will contain flow rate and pressure values. This equation is useful if we want to combine it with the extrusion screw design equation in order to establish the operating point. However, for the purposes of die design an equation without the flow rate and pressure terms would be more useful and will be developed in the second part.

The following assumptions are made:

- **incompressible fluid:** density is constant
- **Isothermal:** no change in temperature
- **Fully developed fluid:** the velocity profile and pressure gradient are independent of the flow direction.
- **Steady state:** variables do not change with respect to time.
- **Negligible body forces**

We first consider the manifold portion of the problem, which is best represented by flow through a pipe.

Any fluid flow solution must satisfy the mass-balance (continuity) equation, so we start there.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rV_r\right)+\frac{1}{r}\frac{\partial V_\theta}{\partial \theta}+\frac{\partial V_z}{\partial_z}=0$$

To find V_z, we will need to use the equation of motion (momentum balance equation). Again, since $\mathbf{V_r}$ and $\mathbf{V_\theta}$ equal zero, the z component of the momentum balance equation in cylindrical coordinates is used:

$$\rho\left(\frac{\partial V_z}{\partial t}+V_r\frac{\partial V_z}{\partial r}+\frac{V_\theta}{r}\frac{\partial V_z}{\partial \theta}+V_z\frac{\partial V_z}{\partial z}\right)=\frac{-\partial p}{\partial z}\mu\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V_z}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 V_z}{\partial \theta^2}+\frac{\partial^2 V_z}{\partial z^2}\right)+\rho b_z$$

On the left-hand side, $\frac{\partial V_z}{\partial t}=0$ because the flow is steady, the second and third terms are zero because $\mathbf{V_r}$ and $\mathbf{V_\theta}$ equal zero, and the continuity equation tells us that the last term is zero. On the right-hand side, the last three terms are zero since there is no change in the θ-directions, the continuity equations indicates that there is no change in V_z in the z-direction, and the body forces are assumed to be negligible.,

Thus, after integration we obtain:

$$V_z=\frac{r^2}{4\mu}\frac{\partial p}{\partial z}+C_1 r+C_2\,,$$

where C_1 and C_2 are integration constants. We find their values using the boundary conditions, which come from the requirement that the fluid's velocity gradient must be zero at the center of the pipe and fluid velocity must equal the velocity of the pipe where the fluid touches the pipe (no slip condition). The boundary conditions are:

$\left.\frac{\partial V_z}{\partial r}\right|_{r=0} = 0 \Rightarrow C_1 = 0$, $\left.V_z\right|_{r=R} = 0 \Rightarrow C_2 = \frac{-R^2}{4\mu}\frac{\partial p}{\partial z}$, so the velocity distribution is

$$V_z = \frac{1}{4\mu}\frac{\partial p}{\partial z}\left(r - R^2\right).$$

Let's consider the volume flowrate (Q) through the pipe:

$Q = 2\pi\int_0^R rV_z\partial r$, since the velocity term has been developed, the flowrate can be rewritten as

$$Q = \frac{-\pi R^4}{8\mu}\frac{\partial p}{\partial z} \qquad (2.1)$$

Equation 2.1 provides a relationship between the flow rate and the pressure gradient.

Considering a small element in the manifold, we can make a mass balance which for constant density is equivalent to a volume balance:

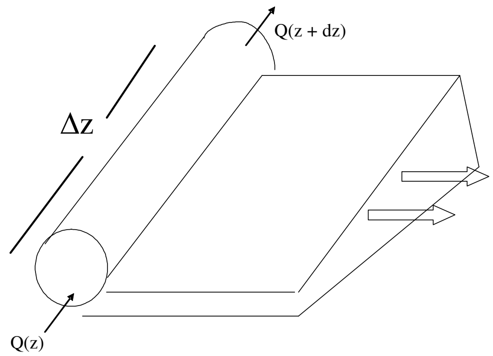


Figure 2.1: Differential element of extruder/die schematic

$$\lim_{\Delta z \to 0} \frac{Q(z) - Q(z + \partial z)}{\Delta z} = q$$

$$\frac{-\partial Q}{\partial z} = q = constant \qquad \text{so,} \qquad \frac{-\partial Q}{\partial z} = C_1$$

therefore,

$$Q = -C_1 z + C_2 \qquad (2.2)$$

To determine the two integration constants, we must use boundary conditions:

$$Q\Big|_{z=0} = Q_T \qquad\qquad Q\Big|_{z=L_D} = 0$$

(Q_T, the total flowrate into the die manifold from the extruder)

Substituting the boundary conditions in to equation (2.2), we get.

$Q(z{=}0) = C_2 = Q_T$

$Q(z{=}L_D) = 0 = -C_1(L_D) + Q_T$

$C_1 = Q_T/L_D$

$Q(z) = \frac{-Q_T}{L_D} z + Q_T$ (2.3a), thus $q = \frac{Q_T}{L_D}$ (2.3b)

Substituting equation (2.3a) into equation (2.1) we get:

$$Q_T\left(1 - \frac{z}{L_D}\right) = \frac{-\pi R^4 \partial p}{8\mu \partial z}$$

Integrating with respect to z and using boundary conditions we obtain the pressure profile of the fluid within the die manifold.

$$P(z) = -\frac{8\mu Q_T}{\pi R^4} z + \frac{8\mu Q_T}{\pi R^4}\left(\frac{z^2}{2L_D}\right) + C$$

considering the pressure at the entrance to the manifold that is:

$P(z = 0) = P_o$ (P_o, inlet pressure into the manifold)

we get:

$C = P_o$

and thus:

$$P(z) = -\frac{8\mu Q_T}{\pi R^4} z + \frac{8\mu Q_T}{\pi R^4}\left(\frac{z^2}{2L_D}\right) + P_o \qquad (2.4)$$

We now look at the land portion of the die whose geometry is best represented as slit flow, as shown in Figure 2.2:

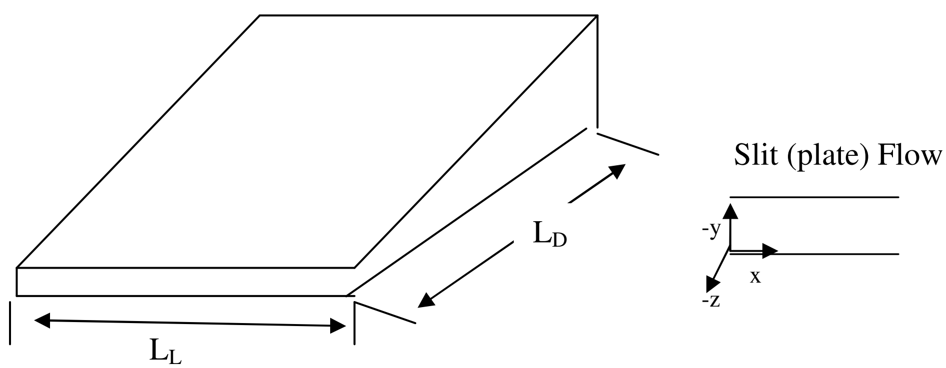


Figure 2.2: Land portion of the die (slit flow)

Assumptions:

- $\frac{\partial}{\partial z} = V_z = 0$ (Lubrication Approximation)
- $V_y = 0$
- Negligible body forces
- Steady State

The continuity equation, in Cartesian coordinates,

$$\frac{\partial p}{\partial t}+\frac{\partial}{\partial x}(\rho V_x)+\frac{\partial}{\partial y}(\rho V_y)+\frac{\partial}{\partial z}(\rho V_z)=0$$

Which gives $\frac{\partial V_x}{\partial x}=0$.

The equation of motion, in Cartesian coordinates,

$$\rho\left(\frac{\partial V_x}{\partial t}+V_x\frac{\partial V_x}{\partial x}+V_y\frac{\partial V_x}{\partial y}+V_z\frac{\partial V_x}{\partial z}\right)=\frac{-\partial p}{\partial x}+\mu\left(\frac{\partial^2 V_x}{\partial x^2}+V_y\frac{\partial^2 V_x}{\partial y^2}+V_z\frac{\partial^2 V_x}{\partial z^2}\right)+\rho b_x$$

After applying the appropriate assumptions and integrating we get:

$$V_x=-\frac{1}{\mu}\frac{P(z)}{L_L}\frac{y^2}{2}+C_1 y+C_2.$$

To determine the two integration constants, we use the no slip boundary condition at the two die surfaces.

$$V_x=-\frac{1}{2\mu}\frac{P(z)}{L_L}\left(y^2-h(z)y\right) \qquad (2.5)$$

Further analyzing the flow between the plates, we consider the flowrate per unit width:

$q = \int_{0}^{h(z)} V_x \partial y$, substituting equation 2.5,

$$q = \frac{P(z)h^3(z)}{12\mu L_L} \qquad \Rightarrow \qquad h^3(z) = \frac{12\mu L_L q}{P(z)} \qquad (2.6)$$

The flow out of the die lips, q (see figure 2.1), must be constant to produce a uniform film thickness. The flow rate out of the die lips equals the flow rate coming into the extruder, along the z-direction. Therefore, we substitute 2.3b into 2.6 to get:

$h^3(z) = \dfrac{12\mu L_L\left(\dfrac{Q_T}{L_D}\right)}{P(z)}$, since we determined P(z) earlier in equation 2.4, the die design equation becomes:

$$h(y) = \left[\frac{12\,\mu L_L Q_T}{L_D\left[-\dfrac{8\,\mu Q_T L_D}{\pi R^4}\left(\dfrac{z}{L_D} - \dfrac{z^2}{2\,L_D{}^2}\right) + P_o\right]_o}\right]^{\frac{1}{3}} \qquad (2.8)$$

2.2 OTHER APPROACH: FLOW RATE AND PRESSURE INDEPENDENT EQUATION

We will now derive an equation without flow rate and pressure terms. This equation will be more useful for die design purposes. However it is important to note that they are both equivalent.

Let h(z) = K, therefore, for slit flow, the flow rate per unit width is:

$$q = \frac{K^3 P}{12\mu L} = constant$$

We now take the derivative with respect to z, to relate the flow rate per unit width to the pressure gradient and we get:

$$\frac{dq}{dz} = \left(\frac{1}{12\mu L}\right)\left\{P3K^2\frac{dK}{dz} + K^3\frac{dP}{dz}\right\} = 0$$

We want the flow rate per unit width to be independent of z, to make sure we get a film of uniform thickness out of the die. Thus the pressure gradient needs to be:

$$\frac{-dP}{dz} = \frac{36q\mu L}{K^4}\frac{dK}{dz} \qquad (2.9)$$

Now we look at the flow in the manifold,

$$Q = \frac{\pi R^4}{8\mu}\left(\frac{-dP}{dz}\right)$$

Also we know that:

$$Q = q(W - z)$$

Thus we get:

$$q(W - z) = \frac{\pi R^4}{8\mu}\left(\frac{-dP}{dz}\right)$$

And the pressure gradient becomes:

$$\frac{-dP}{dz} = \frac{8\mu q(W - z)}{\pi R^4}$$

Substituting (2.9) into the above equation we get:

$$\frac{8\mu q(W - z)}{\pi R^4} = \frac{36q\mu L}{K^4}\frac{dK}{dz}$$

And thus the die equation becomes:

$$K = \left\{ \frac{(W-z)^2}{3\pi R^4 L} + C \right\}^{\frac{-1}{3}} \qquad (2.10)$$

Rewriting equation 2.10 in terms of the variables used in the previous section we get:

$$h(z) = \left\{ \frac{(L_D - z)^2}{3 L_l \pi R^4} + C \right\}^{\frac{-1}{3}}$$

Now using as boundary condition to evaluate the integration constant, the die thickness at the entrance which should be its minimum value:

z = 0, h = h_o = h_{min}

And we get for the die design equation:

$$\frac{1}{h^{\,3}} = \frac{\left(L_D - z\right)^2}{3 L_L \pi R^4} + \frac{1}{h_{\min}^3} - \frac{L_D^2}{3 L_L \pi R^4} \qquad (2.11)$$

At z = L_D, h = h_{max}

Now, a relationship between the largest and smallest die thickness can be obtained:

$$\frac{1}{h_{\max}^3} = \frac{1}{h_{\min}^3} - \frac{L^2{}_D}{3 L_L \pi R^4} \qquad (2.12)$$

Note that equation 2.10 is equivalent to equation 2.8. If we substitute in equation 2.8 the value of the pressure at the entrance of the manifold where h=hmin:

$$P_o = \frac{Q_T 12 \mu L_L}{W h^3 o}$$

We can show that equation 2.8 becomes 2.11. Note that equations 2.10 and 2.11 don’t contain any material or process parameters. It contains only die geometric parameters. We will see that for the power law case in the next section, the only material parameter that remains is the power law exponent.

CHAPTER 3

DIE DESIGN FOR A POWER LAW FLUID

Here we develop the die design equation for the power law fluid and compare it to experimental results of die opening. For clarity, as in the case of the Newtonian fluid, we first develop an equation containing flow rate and pressure terms and in the second part we develop the equation without flow rate and pressure terms.

3.1 PRESSURE AND FLOW RATE EQUATION

As we did in chapter 2, we begin by representing the manifold section of the die with pressure flow through a tube. The velocity field for the flow of a power law fluid in a tube is given by:

$$V_z(r) = (\frac{R\Delta P}{2ml})^2 \left[1-(\frac{r}{R})^{s+1}\right] \qquad (3.1)$$

The equation above can be integrated to obtain an expression for the flow rate:

$$Q = (\frac{\pi R^3}{s+3})(\frac{r}{2m})^s(-\frac{\partial P}{\partial z})^s \text{, where s= 1/n} \qquad (3.2)$$

To determine the pressure profile, we consider the flow balance in the differential element, figure 2.1. As obtained earlier,

$$Q(z) = \frac{Q_T}{L_D} z + Q_T \qquad (3.3)$$

Therefore, substituting (3.3) into (3.2) we get:

$$Q_T\left(1-\frac{z}{L_D}\right) = \frac{\pi R^3}{s+3}\left(\frac{R}{2m}\right)^s\left(\frac{-\partial P}{\partial z}\right)^s$$

Thus the pressure gradient in the manifold becomes:

$$\frac{-\partial P}{\partial z} = \left[\frac{Q_T \left(1 - \frac{z}{L_D}\right)}{\frac{\pi R^2}{s+3}} \right]^n \frac{2m}{R}$$

$$\frac{-\partial P}{\partial z} = \left[\frac{Q_T \left(1 - \frac{z}{L_D}\right)}{B} \right]^n \frac{2m}{R}, \quad \text{where } B = \frac{\pi R^2}{s+3}$$

$$\frac{-\partial P}{\partial z} = \left(K - \frac{Q_T^n z^n}{L_D^n B^n} \right)\left(\frac{2m}{R} \right), \quad \text{where } K = \frac{Q_T}{B^n} = \frac{Q_T^n}{\left(\frac{\pi R^2}{s+3} \right)^n}$$

$$\frac{-\partial P}{\partial z} = AK - Dz^n, \quad \text{where } A = \frac{2m}{R}, \qquad D = \frac{Q_T^n}{L_D^n B^n}$$

$$\int \partial P = \int \left(Dz^n - AK \right) \partial z$$

$$P(z) = \frac{D}{n+1} z^{n+1} - AKz + C$$

To determine the integration constant, we know that the pressure at the end of the extruder (z=0) is equal to P_0, therefore, $C=P_o$.

The pressure profile in the manifold is represented by:

$$P(z) = \frac{Q_T^n (s+3)^n}{L_D (\pi R^2)^n} z^{n+1} - \frac{2m}{R} \frac{Q_T^n (s+3)^n}{(\pi R^2)^n} z + P_o \qquad (3.4)$$

We will now consider flow between two parallel plates (slit flow) for a power law fluid:

$$Q = \frac{Wh^2}{2(s+2)} \left(\frac{h \Delta p}{2mL} \right)^s \qquad (3.5)$$

However, the flow rate changes in the z-direction and what needs to be kept constant is the flow rate per width q. So if we divide equation 3.5 by the width of the die, L_D, q can be represented as:

$$q = \frac{Q}{L_D} = \frac{h^2(z)}{2(s+2)} \left(\frac{h(z) \Delta P}{2mL_L} \right)^s \qquad (3.5)$$

The differential element analysis performed in chapter 2, gave us:

$$q = -\frac{\partial Q}{\partial z} = \frac{Q_T}{L_D} \qquad (3.6)$$

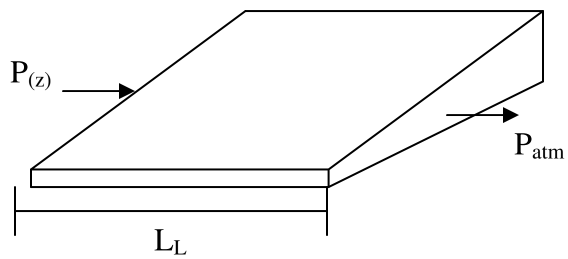


Figure 3.1: Geometry of die illustrating the pressure in the manifold

From figure 3.1, we see that

$$\frac{\Delta P}{L} = \frac{P(z) - P_{atm}}{L_L} \cong \frac{P(z)}{L_L}$$

Therefore, (3.5) becomes

$$q = \frac{h^2(z)}{2(s+2)} \left(\frac{h(z)P(z)}{2mL_L} \right)^s \quad (3.7a)$$

$$h(z) = \frac{(2mL_L)^{\frac{1}{2n+1}} (2q(s+2))^{\frac{n}{2n+1}}}{P(z)^{\frac{1}{2n+1}}} \qquad (3.7b) \qquad \text{where } s = 1/n$$

Substituting (3.6) into (3.7b)

$$h(z) = \frac{(2mL_L)^{\frac{1}{2n+1}} \left(2\frac{Q_T}{L_D}(s+2) \right)^{\frac{n}{2n+1}}}{P(z)^{\frac{1}{2n+1}}} \qquad (3.8)$$

Substituting (3.4) into (3.8) we get the die design equation:

$$h(z) = \left[\frac{(2mL_L)\left(2\dfrac{Q_T}{L_D}(s+2)\right)^n}{\dfrac{Q_T^n(s+3)^n}{(\pi R^2)^n}\left[\dfrac{z^{n+1}}{L_D} - \dfrac{2m}{R}z\right] + P_o} \right]^{\frac{1}{2n+1}} \qquad (3.9)$$

Equation 3.9 describes the die lip opening in terms of process variables.

If equation 3.9 is independent of flow rate and material variables like the Newtonian case, we should get the same values independent of temperature. This is done below, where we used the values for the material given in appendix A. To develop a pressure versus flow rate, we used equation (3.7a), and applied it at the beginning of the slit (z=0). This is similar of what we did in the Newtonian case to demonstrate that both equations were the same. We will check its dependence on temperature using typical processing temperatures ranging between 355C and 390C.

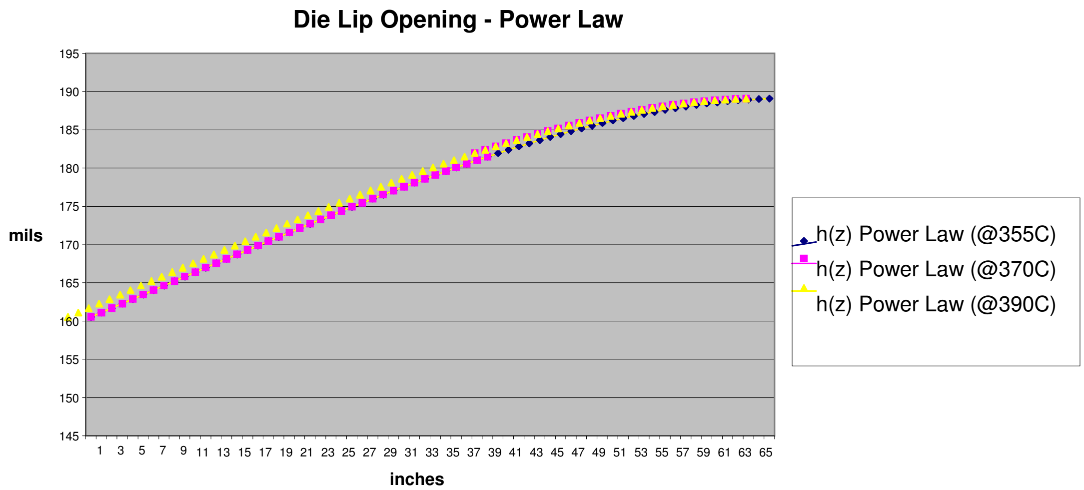


Figure 3.2: Die Lip Opening profile for power law fluid, at processing temperatures, using equation 3.9.

As shown in figure 3.2, there is very little difference in the die lip opening profiles at different temperatures; therefore, we will assume there is no temperature dependence.

3.2 OTHER APPROACH: FLOW RATE AND PRESSURE INDEPENDENT EQUATION

Again, starting with equation 3.5, the flow rate per area in power law slit flow we get:

$$q = \frac{Q}{W} = \frac{h^2(z)}{2(s+2)}\left(\frac{h(z)\Delta P}{2mL_L}\right)^s$$

And thus the pressure gradient is given by:

$$\frac{-\partial p}{\partial z} = 2^n (s+2)^n (2mL_L) h(z)^{-2n-2} \frac{\partial h(z)}{\partial z} \qquad (3.10)$$

At this point, let's revisit some equations derived earlier.

The differential element analysis, in chapter 2, led to

$$Q(z) = \frac{Q_T}{L_D} z + Q_T = \frac{Q_T}{L_D}(L_D - z) \qquad (3.11)$$

From this analysis, we know

$q = -\dfrac{\partial Q}{\partial z} = \dfrac{Q_T}{L_D}$, substituting into (3.11) we get:

$$Q = q(L_D - z)$$

Further, from the pipe flow analysis (representing flow through the manifold)

$$Q = (\frac{\pi R^3}{s+3})(\frac{r}{2m})^s(-\frac{\partial P}{\partial z})^s$$

Therefore,

$$\frac{q^n (L_D - z)^n}{\left(\frac{\pi R^3}{s+3}\right)^n \left(\frac{R}{2m}\right)} = \frac{-\partial p}{\partial z} \qquad (3.12)$$

Now having two expressions for $\frac{-\partial p}{\partial z}$ (equations 3.10 and 3.12), setting them equal to one another will eliminate the pressure term.

Let $A = \frac{1}{2(s+2)}\left(\frac{1}{2mL_L}\right)^s$ and $B = \left(\frac{\pi R^3}{s+3}\right)\left(\frac{R}{2m}\right)^s$

Setting 3.10 equal to 3.12

$$(2n+1)\frac{q^n}{A^n}(h(z))^{-2n-1}\frac{\partial h(z)}{\partial z} = \frac{q^n (L_D - z)^n}{B^n}$$

Integrating with respect to dz

$$h(z) = \left[\frac{A^n}{B^n} \frac{(L_D - z)^{n+1}}{n+1} + C \right]^{\frac{-1}{2n+1}}$$, where $C = C_1 + C_2$

The boundary condition used to determine the integration constant

$z = 0$, $h(z) = h(z)_{\min}$

$$h(0) = h(z)_{\min} = \left[\frac{A^n}{B^n} \frac{L_D^{n+1}}{n+1} + C \right]^{\frac{-1}{2n+1}}$$

$$h(z)_{\min}^{-(2n+1)} = \left[\frac{A^n}{B^n} \frac{L_D^{n+1}}{n+1} + C \right]$$

$C = h(z)_{\min}^{-(2n+1)} - \dfrac{A^n}{B^n} \dfrac{L_D^{n+1}}{n+1}$, therefore

$$h(z) = \left[\frac{-A^n}{B^n} \frac{L_D^{n+1}}{n+1} + h_{\min}(z)^{-(2n+1)} + \frac{A^n}{B^n} \frac{(L_D - z)^{n+1}}{n+1} \right]^{\frac{1}{-(2n+1)}} \qquad (3.13)$$

Therefore, equation 3.13 describes the die lip opening for a die assuming the fluid to be a power law fluid. Equation 3.13 doesn't have pressure or flow rate terms. The only material term that appears is the power law exponent (n). Since this n does not depend of temperature in our case, this is why the equation for h was not affected by temperature. Recall than for the Newtonian case, no material parameter appears.

Equation 3.13 can then be applied to relate the hmax to hmin, just as we did for the power law case:

$$\frac{1}{h_{\max}^{2n+1}} = \frac{1}{h_{\min}^{2n+1}} - \frac{(s+3)^n L_D^{n+1}}{(n+1)2^n (s+2)^n L_L \pi R^{3n+1}} \tag{3.14}$$

3.3 EXPERIMENTAL VERIFICATION

To further ensure that the derived equation is applicable to processing conditions and manufacturing requirements, the maximum die lip opening (H_{max}), as determined by equation 3.9, and the maximum lip opening on the current manufacturing die were compared. The H_{min} used in equation 3.9 to calculate the theoretical H_{max} were .07", .15", and .22" for the 78" die, 67" die, and 60" die, respectively.

	Maximum lip opening (Hmax)	
	Theory (in)	Actual Manufacturing (in)
78" die	.073	.074
67" die	.161	.160
60" die	.235	.234

Table 3.1: Comparison of die lip opening as determined by the derived equation (equation 3.9, at 355C) and the current manufacturing die.

For all three of the dies used at DuPont to manufacture FEP® film, the experimental die lip opening and the one predicted by the derived equation are very close. This is a positive result for the derived equation. The minimum lip opening used in actual production was used in equation 3.9 to determine the practical maximum lip opening.

CHAPTER 4

EFFECT OF MATERIAL PARAMETERS ON THE DIE OPENING

In the last chapter we derived an equation, to predict how the die thickness should be adjusted as a function of the die width, to make sure that the flow rate per unit width out of the die is constant. This will provide us with a uniform film thickness out of the die. The analysis showed that the die profile was independent of temperature. As seen in the derived equation, the only material parameter that appears in the die design equation is the power law index. Thus as long as the plastic under consideration can be represented by the power law equation and the power law index can be considered independent of temperature, the above result will hold.

Thus for a power law plastic, in order to determine the effect of material on the die thickness, we need only to evaluate what is the effect of the power law index on the value of the die thickness. Figures 4.1, 4.2 and 4.3, show how Hmax varies as a function of Hmin for the three dies discussed in the previous chapter. Figure 4.1 is for the 60” die, figure 4.2 for the 67” die and finally figure 4.3 for the 78” die.

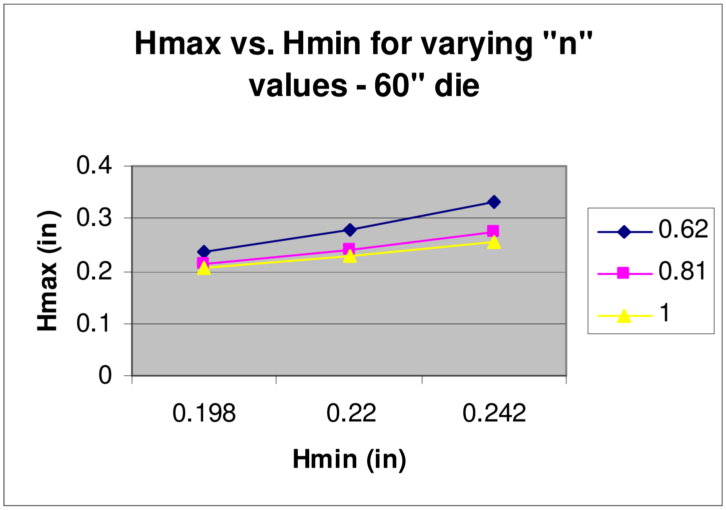


Figure 4.1: the range between Hmax and Hmin for varying powerlaw index for the 60” die variables for equation 3.9

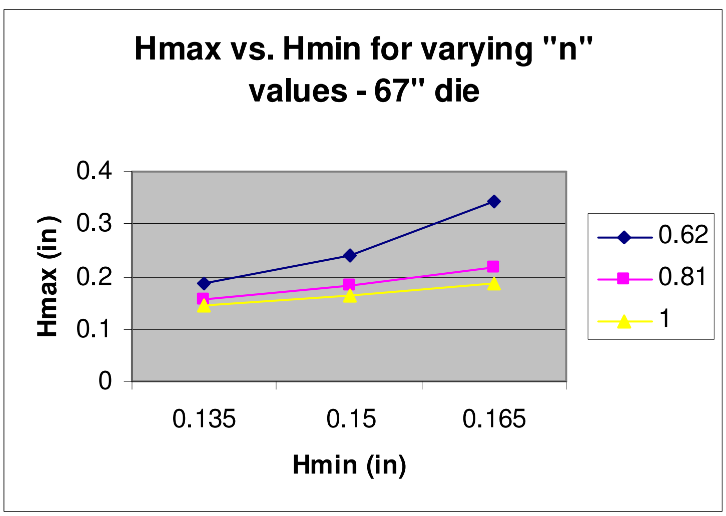


Figure 4.2: the range between Hmax and Hmin for varying powerlaw index for the 67” die variables in equation 3.9

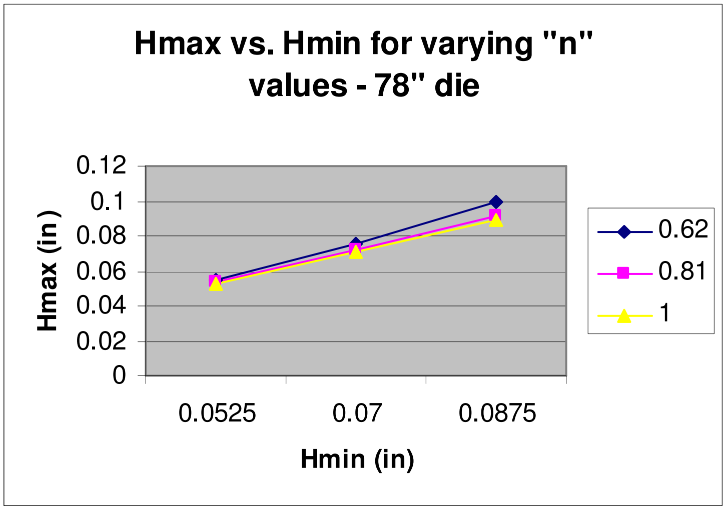


Figure 4.3: the range between Hmax and Hmin for varying powerlaw index for the 78” die variables in equation 3.9

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

In this work, the equation for the die lip opening of a polymer film manufacturing die, in order to obtain a uniform film thickness was derived. Parameters for three different size dies (60”, 67” and 78”) were used to test the validity of the equation for the manufacturing conditions using in DuPont Teflon® Films business. It was determined that the die opening was independent of temperature as long as the plastic can be represented by the power law and the power law exponent can be assumed to be independent of temperature. This is not a bad assumption for most plastic materials at the processing conditions.

The charts presented in Section 4 show the effect of the value of the power law index on the die opening.

Future work can include optimizing the factors that affect the die opening. One criterion could be to find out what values minimize the difference between Hmax and Hmin. A possible way to perform this evaluation is through the use of response surface methodology (RSM). RSM is a collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes.

The work in this thesis, assumed isothermal conditions, and a natural extension would be to relax this assumption which would require combining the balance of linear momentum with the energy balance. Also, combining the extruder equation with the die equation to establish the operating point would be useful in optimizing the process.

APPENDIX

RHEOLOGICAL PARAMETERS

Using DuPont® manufactured FEP100 grade resin, the rheology was measured on Rheometrics ARES Rheometer at DuPont's Experimental Station Laboratory by Liz Wolf, Oct 2002 [9]. The measurements were done using dynamic testing from which the values of G' and G" for several frequencies were measured. The absolute value of the complex viscosity was then calculated [8]. We then assumed that the absolute value of the complex viscosity versus the frequency in radians/sec was equivalent to the steady shear viscosity versus shear rate in 1/sec [8]. This was done fro three temperatures (360C, 340C, and 320C) as shown in table 2.

Based on this experimental data, the power-law model was used to determine the rheological parameters used in the calculations described in this report as shown below.

Power law model: $\eta = m \dot{\gamma}^{n-1}$, where the consistency index, $m = m_o e^{-bT} \dot{\gamma}^{n-1}$

Thus, the viscosity becomes:

$\eta = m_o e^{-bT} \dot{\gamma}^{n-1}$, where gamma dot = shear rate (1/s), and T is Temperature (Kelvin) (A.1).

Table A.1 shows the values of the viscosity predicted by the equation developed.

	Temperature	Frequency	G'	G"	Eta*	Predicted Eta*
	Kelvins	**rad/s**	**Pa**	**Pa**	**Pa-s**	
	633.15	100.00	1.23E+05	1.29E+05	1.79E+03	2.21E+03
	633.15	63.10	8.86E+04	1.09E+05	2.22E+03	2.40E+03
	633.15	39.81	6.12E+04	8.79E+04	2.69E+03	2.62E+03
	633.15	25.12	4.05E+04	6.86E+04	3.17E+03	2.85E+03
	633.15	15.85	2.58E+04	5.18E+04	3.65E+03	3.10E+03
T = 360 C	633.15	10.00	1.57E+04	3.80E+04	4.11E+03	3.38E+03
	633.15	6.31	9.22E+03	2.71E+04	4.54E+03	3.68E+03
	633.15	3.98	5.22E+03	1.88E+04	4.91E+03	4.01E+03
	633.15	2.51	2.86E+03	1.28E+04	5.22E+03	4.37E+03
	633.15	1.58	1.52E+03	8.56E+03	5.48E+03	4.76E+03
	633.15	1.00	7.43E+02	5.63E+03	5.67E+03	5.18E+03
	633.15	0.63	3.75E+02	3.66E+03	5.83E+03	5.64E+03
	633.15	0.40	1.86E+02	2.36E+03	5.95E+03	6.14E+03
	633.15	0.25	9.16E+01	1.51E+03	6.03E+03	6.69E+03
	633.15	0.16	4.51E+01	9.62E+02	6.08E+03	7.29E+03
	633.15	0.10	2.19E+01	6.08E+02	6.09E+03	7.94E+03
	613.15	100.00	1.41E+05	1.36E+05	1.96E+03	2.73E+03
	613.15	63.10	1.03E+05	1.16E+05	2.47E+03	2.98E+03
	613.15	39.81	7.28E+04	9.58E+04	3.02E+03	3.24E+03
	613.15	25.12	4.92E+04	7.62E+04	3.61E+03	3.53E+03
	613.15	15.85	3.19E+04	5.86E+04	4.21E+03	3.84E+03
T = 340 C	613.15	10.00	1.99E+04	4.37E+04	4.80E+03	4.19E+03
	613.15	6.31	1.19E+04	3.17E+04	5.36E+03	4.56E+03
	613.15	3.98	6.88E+03	2.23E+04	5.87E+03	4.97E+03
	613.15	2.51	3.84E+03	1.54E+04	6.30E+03	5.41E+03
	613.15	1.58	2.08E+03	1.04E+04	6.67E+03	5.89E+03
	613.15	1.00	1.04E+03	6.86E+03	6.94E+03	6.42E+03
	613.15	0.63	5.33E+02	4.49E+03	7.16E+03	6.99E+03
	613.15	0.40	2.69E+02	2.91E+03	7.35E+03	7.61E+03
	613.15	0.25	1.35E+02	1.88E+03	7.50E+03	8.29E+03
	613.15	0.16	6.71E+01	1.20E+03	7.61E+03	9.03E+03
	613.15	0.10	3.29E+01	7.69E+02	7.69E+03	9.83E+03

Table A.1: Table of data obtained from Rheometrics ARES Rheometer

Table A.1 (continues)

	Temperature	Frequency	G'	G"	Eta*	Predicted Eta*
	Kelvins	rad/s	Pa	Pa	Pa-s	
T = 320 C	593.15	100.00	1.65E+05	1.45E+05	2.20E+03	3.38E+03
	593.15	63.10	1.24E+05	1.26E+05	2.81E+03	3.69E+03
	593.15	39.81	8.94E+04	1.06E+05	3.49E+03	4.01E+03
	593.15	25.12	6.20E+04	8.65E+04	4.24E+03	4.37E+03
	593.15	15.85	4.12E+04	6.79E+04	5.01E+03	4.76E+03
	593.15	10.00	2.63E+04	5.16E+04	5.79E+03	5.19E+03
	593.15	6.31	1.61E+04	3.81E+04	6.55E+03	5.65E+03
	593.15	3.98	9.50E+03	2.73E+04	7.26E+03	6.15E+03
	593.15	2.51	5.40E+03	1.90E+04	7.88E+03	6.70E+03
	593.15	1.58	2.97E+03	1.30E+04	8.41E+03	7.30E+03
	593.15	1.00	1.59E+03	8.71E+03	8.86E+03	7.95E+03
	593.15	0.63	7.96E+02	5.74E+03	9.18E+03	8.65E+03
	593.15	0.40	4.05E+02	3.74E+03	9.45E+03	9.42E+03
	593.15	0.25	2.06E+02	2.42E+03	9.69E+03	1.03E+04
	593.15	0.16	1.04E+02	1.56E+03	9.87E+03	1.12E+04
	593.15	0.10	5.28E+01	1.00E+03	1.00E+04	1.22E+04

Table A.1: Table of data obtained from Rheometrics ARES Rheometer

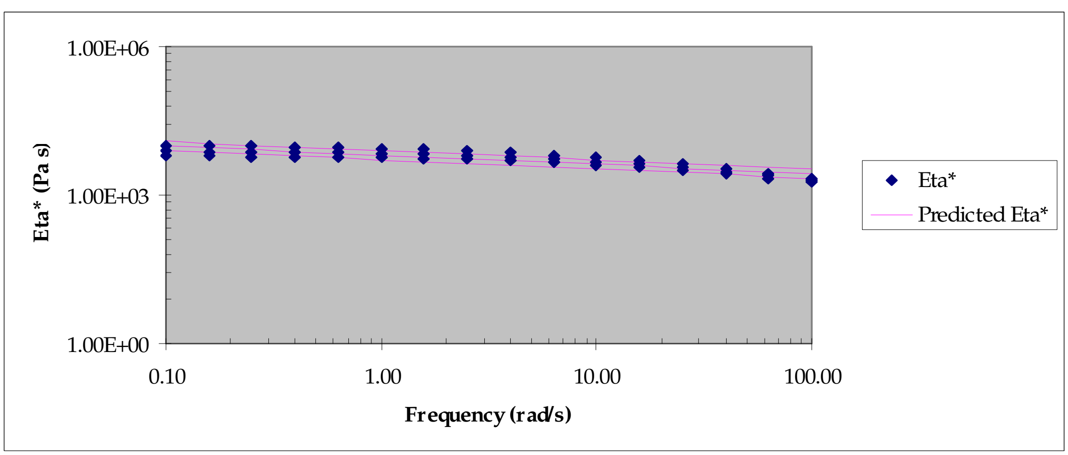


Figure A.1: Comparison of experimental data and predicted data for Eta

The power law index, n, was determined by taking the natural log of equation A.1 and A.2, plotting the natural log of the shear rate against the natural log of Eta*.

$$\ln\eta = \ln(m_o e^{-bT}\dot{\gamma}^{n-1}) \Rightarrow \qquad \ln\eta = -bT + \ln m_o + (n-1)\ln\dot{\gamma} \qquad \text{(A.2)}$$

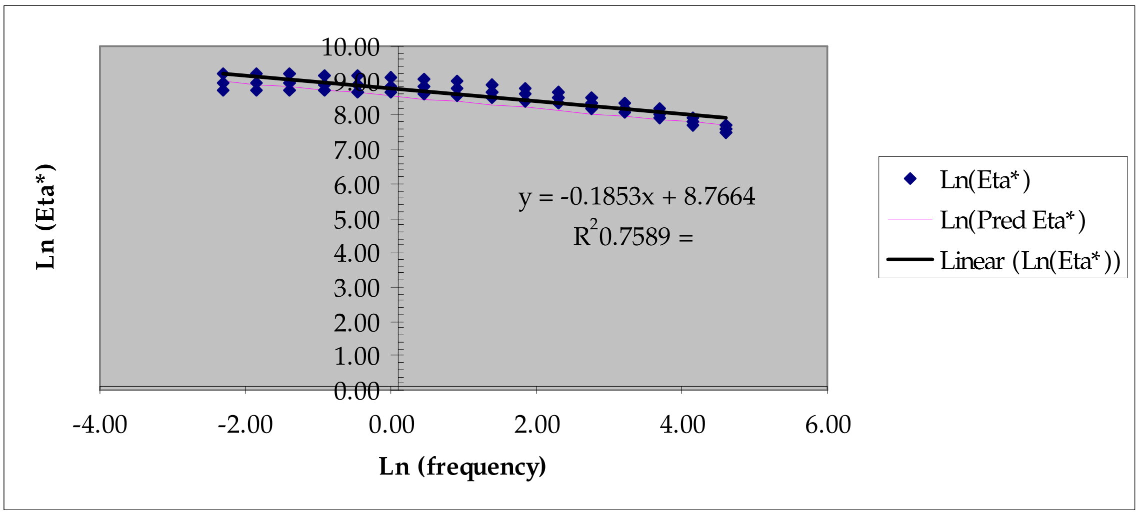


Figure A.2: Natural log of Eta vs. Natural log of Eta (actual and predicted)

The slope of the best fit line linear (ln(Eta*)), in figure A.2, is equal to n-1. Therefore,

$n-1 = -.19$ and $n = 0.81$

And if we let $m = m_o e^{-bT}$ (A.5), then $\ln m = -bT + \ln m_o$ (A.3), then the y-intercept of the best fit line, in figure A.2, represents ln(m). Therefore, Using equation A.3, if we plot ln m verses T, the slope represents “b” and the intercept represents “ln m_o.

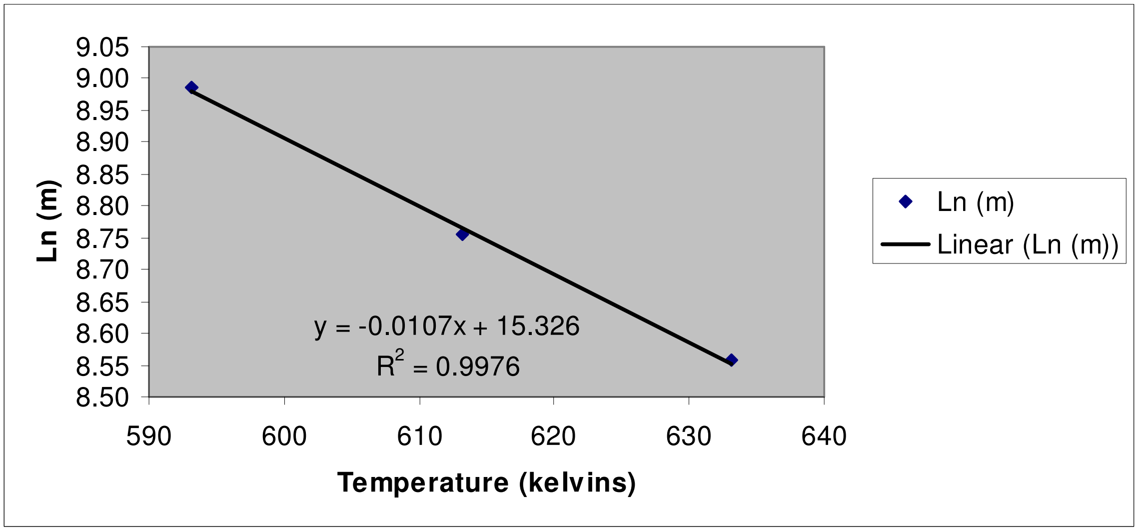


Figure A.3: Natural log of m vs. Temperature

Therefore, the power law parameters are:

Power Law Parameters				
m_0 Pa- s^n	b 1/kelvin	n	SSE	Average Error
4.53E+06	1.07E-02	0.81	3.67E+07	13.98%

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