Simulation and Design of Extrusion Dies

Kirubel Bogale

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Author:	Kirubel Bogale
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Supervisor (Arcada):	Mathew Vihtonen
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Abstract:

The aim of this engineering thesis was to design and simulate a die for a rectangular profile. The project consisted of studying melt flow characteristics of plastics and how the die structure should be set in order to get the desired shape. After the die has been designed on 3D Solid edge design software it was simulated on COMSL flow simulation software. On the simulation software it was easy to study how the melt flows and in which part of the die is the shear stress and strain strong and weak.

The drag flow and pressure flow were then extracted from the screw parameters which lead into the calculation of the operation point and the operating pressure for the die.
It was also possible to calculate the mass flow rate and the velocity drop. And finally die optimization of die profile for rectangular shape was done.

Keywords:	Extrusion, Comsol, Solid edge, flow rate, output, density operating point, Die design, Viscosity
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Nomenclature

P = pressure (N)

Q_d = Drag flow (m^3/s)

Q_p = Pressure flow (Pa)

N = Screw revolution (rpm)

H = Channel depth of the screw (m)

$\emptyset$ = Helix angle of screw

L = length of the screw (m)

D = diameter of the screw (m)

R = die radius (m)

L_d = length of the die (m)

η = viscosity (Pa.s)

γ = Shear rate (S^{-1})

τ = Shear stress

n = Power law index

O_{op} = Operating point

P_{op} = Pressure at the operating point (Pa)

ρ = Melt density (kg/m^3)

$\dot{m}$ = Mass flow rate

Glossary

Viscosity: describes a fluid that is thick, sticky and does not flow easily

Viscoelastic: a plastic melt having both viscous and elastic properties

Thermoplastics: polymers that turns to liquid when heated and solidifies when cooled

Pressure flow: the flow of the polymer melt caused by pressure difference

Shear stress: tangential force divided by area

Shear rate: Velocity gradient measured in s-1

Shear thinning: reduction of viscosity as shear rate increases

Shear thickening: describes a fluid with increasing viscosity as shear rate increases

1 INTRODUCTION

1.1 Background

One of the keys to successful profile extrusion is combining good profile cross sectional designs with good die design. Frequently, die design for profile extrusion is done using trial and error methods in-house by the company producing the profile. A good die designer can machine the correct die shape to produce the specified profile in three to four die cuttings or modifications, while an inexperienced die designer may have to machine seven to eight dies to obtain the desired profile. Some companies specialize in computer-aided die designs based on computer modeling. With the desired profile cross section defined, the rheological parameters (viscosity versus shear rate, extension modulus and flow modulus) for the resin and the throughput rate, computer programs can design the die cross section required, while predicting the pressure drops, melt temperature, and flow profiles within the die. Richardson [1]

The die has to be properly designed to have uniform flow and pressure drops in all the legs of the profile. Improperly designed dies can lead to severe warpage problems associated with the profiles. Higher polymer flow rates in one section of the die compared to another will result in different molecular orientation. This causes different shrinkage characteristics from one section to the other. Melt temperature in all channels needs to be similar to prevent one profile section from being hotter than another. This can lead to differential cooling outside the die and differential shrinkage and warpage. Another factor that can lead to warpage in the final part is different molecular packing in one part of the die versus another, attributed to higher die pressure in one area compared to another. Part areas with higher molecular packing produce less shrinkage compared to other part sections. These factors are normally grouped under a general heading of internal stresses in the final part. And non uniform internal stresses can cause warpage in the final profile because the shrinkage is different between one profile sections relative to another. Richardson [1]

1.2 Objective

The main objectives of this thesis are

1. To design a die using a Solid Edge modeling software for a rectangular profile.
2. To simulate the flow of polymers in the die using Comsol.

3. To calculate the output mass flow rate and the operating point of the die.

2 LITERATURE SURVEY

2.1 Extrusion

One of the most outstanding features of plastics is the ease with which they can be processed. In some cases semi-finished articles such as sheets or rods are produced and subsequently fabricated into shape using conventional methods such as welding or machining. In the majority of cases, however, the finished article, which may be quite complex in shape, is produced in a single operation. The processing stages of heating, shaping and cooling may be continuous (e.g. production of pipe by extrusion) or a repeated cycle of events (e.g. production of a telephone housing by injection moulding) but in most cases the processes may be automated and so are particularly suitable for mass production. There is a wide range of processing methods which may be used for plastics. In most cases the choice of methods is based on the shape of the component and whether it is thermoplastic or thermosetting. It is important therefore that throughout the design process, the designer must have a basic understanding of the range of processing methods for plastics since an ill-conceived shape of design detail may limit the choice of moulding methods. Crawford [2]

Extrusion is a plastic deformation process in which a block of billet is forced to flow by compression through the die opening of a smaller cross-sectional area.

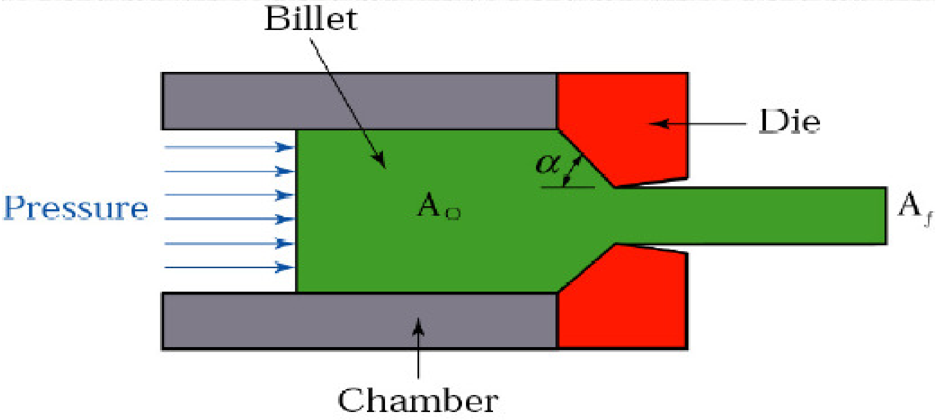


Figure 1 Definition and Principle of Extrusion. Scribd [7].

2.2 Types of Extrusion

Direct extrusion (or Forward Extrusion) – Billet is placed in a chamber and forced through a die opening by a hydraulically driven ram or pressing stem.

Indirect Extrusion – Die moves towards the billet

Hydrostatic Extrusion – The billet is smaller in diameter that the chamber, which is filled with a fluid and the pressure, is transmitted to the billet by a ram.
Scribd [8]

2.3 Extrusion Process and Operation

Extrusion of plastics, like injection molding, is a relatively simple concept, but the design and application of extruders is a complex field. Scribd [6]

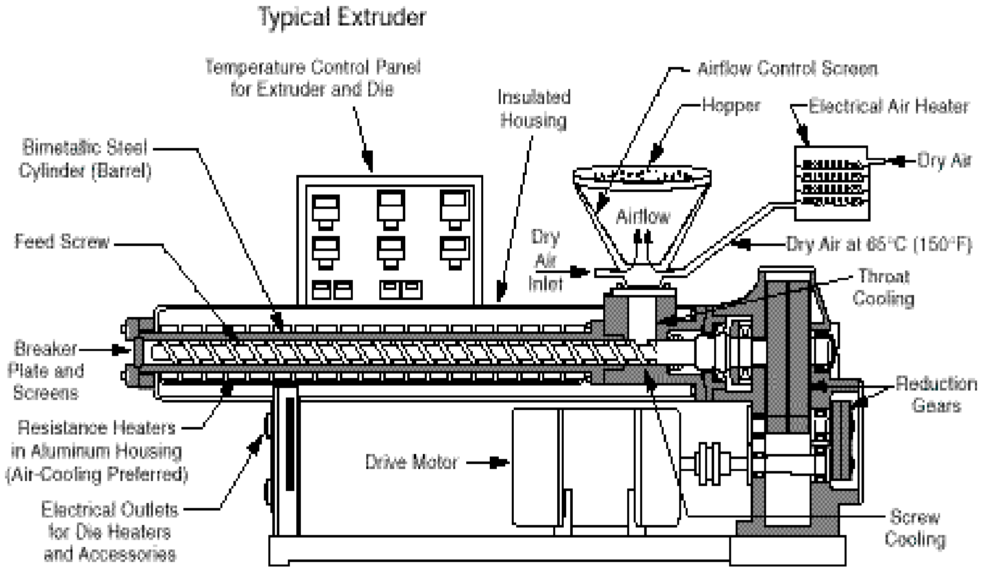


Figure 2 Extrusion Process and Operation. Scribd [7].

2.3.1 Single screw

In injection molding the purpose of the screw extruder is simply to obtain a melt, a dedicated extrusion machine works on the same principle but also must mix, homogenize and melt the material. Higher back pressure may be generated in single screw extrusion machines compared to injection molding machines and the screws may be longer for better mixing. In combination with the barrel, the purpose of the screw is to convert solid material to the melt zone, melt, and mix and pump material to the die in an efficient manner. The screw design and length of screw will depend on the polymer being processed as well as the application. Increasing the capacity by "pumping" more material through the screw can be done by increasing the length of the screw and or flight dept, but this only helps to a point. For hard to melt materials or to increase melt homogeneity, a second or third flight may be added to a screw in order to prevent unmelted material from reaching the die. Scribd [8]

2.3.2 Mechanism of Flow

As the plastic moves along the screw, it melts by the following mechanism. Initially a thin film of molten material is formed at the barrel walls. As the screw rotates it scrapes this film off and molten plastic moves down the front face of the screw flight. When it reaches the core of the screw it sweeps up again, setting up a rotary movement in front of the leading edge of the screw flight. Initially the screw flight contains solid granules but these tend to be swept into the molten pool by the rotary movement. As the screw rotates, the material passes further along the barrel and more and more solid material is swept into the molten pool until eventually only melted material exists between the screw flights. Crawford [2]

As the screw rotates inside the barrel, the movement of the plastic along the screw is dependent on whether or not it adheres to the screw and barrel. In theory there are two extremes. In one case the material sticks to the screw only and therefore the screw and material rotate as a solid cylinder inside the barrel. This would result in zero output and is clearly undesirable. In the second case the material slips on the screw and has a high resistance to rotation inside the barrel. This results in a purely axial movement of the melt and is the ideal situation. In practice the behavior is somewhere between these limits as the material adheres to both the screw and the barrel. The useful output from the extruder is the result of a drag flow due to the interaction of the rotating screw and stationary barrel. This is equivalent to the flow of a viscous liquid between two parallel plates when one plate is stationary and the other is moving. Superimposed on this is a flow due to the pressure gradient which is built up along the screw. Since the high pressure is at the end of the extruder the pressure flow will reduce the output. In addition, the clearance between the screw flights and the barrel allows material to leak back along the screw and effectively reduces the output. This leakage will be worse when the screw becomes worn. Crawford [2]

The external heating and cooling on the extruder also plays an important part in the melting process. In high output extruders the material passes along the barrel so quickly that sufficient heat for melting is generated by the shearing action and the barrel heaters are not required. In these circumstances it is the barrel cooling which is critical if excess heat is generated in the melt. In some cases the screw may also be cooled. This is not intended to influence the melt temperature but rather to reduce the frictional effect between the plastic and the screw. In all extruders, barrel cooling is essential at the feed pocket to ensure an unrestricted supply of feedstock. Crawford [2]

2.3.3 Die Design

Die characteristic for rectangular cross section can be extracted using the following formula. Where

$$Q = KP \tag{2.0}$$

Where $K = Fbd^3/12\eta L_d$

Therefore

$$Q = (Fbd^3/12\eta L_d) * P \tag{2.1}$$

Where b is the greater dimension of the cross-section

d is the least dimension of the cross-section

F is a non-dimensional factor (Flow coefficient).

L_d is the length of the Die.

The flow coefficient can easily be obtained from figure 3

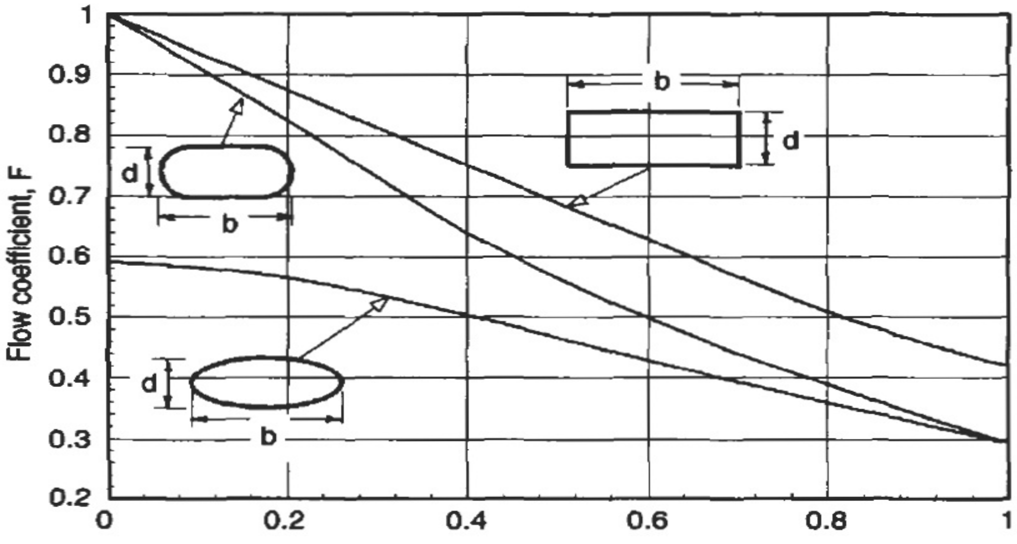


Figure 3. Flow coefficient as a function of channel geometry [Crawford (2, p.260)]

Using equation (2.1) it is possible to modify the expression for the operation pressure to the more general form. Crawford [2]

$$P_{op} = \left\{ \frac{2\pi\eta D^2 NH sin\emptyset cos\emptyset}{\frac{Fbd^3}{3\pi Ld} + \left(\frac{DH^3 \sin^2 \emptyset}{3Ld} \right)} \right\} \tag{2.2}$$

2.3.4 Pressure Gauges

Gauges are simple to install and easy to use. Mechanical gauges do not require any wiring. Gauges are ideal for providing a general indication of processing conditions including contamination build-up on screen packs. Digital gauges can be used to shut down the extruder before rupture disks are blown. [14]

<u>Gauge Types</u>

Mechanical gauges

Mechanical gauge 0150 	Mechanical gauge 0151 	Mechanical gauge with J/t/c 0152 
6" rigid stem	6" rigid stem with 30" flex	6" rigid stem with 30" flex

Digital gauges

Digital gauge 0250	Digital gauge 0251	Digital gauge with J/t/c 0252
6" rigid stem	6" rigid stem with 30" flex	6" rigid stem with 30" flex

2.3.5 Heating Elements

Thermal Corporation's band heaters are made to heat cylinders, such as pipes, barrels, or nozzles of injection molding and extruding machines. Mica band heaters are constructed by winding a resistance wire or ribbon around a sheet of mica, sandwiching that element between two other sheets of mica, and then forming coated steel around the assembly.

Mica-type band heaters have several advantages over other types of band heaters, but the thing that makes them the most used heater in the plastics industry is the combination of reasonable high-watt density capabilities, reasonably high temperature capabilities (900 degrees Fahrenheit), good efficiency, good lifetime and low cost. Google [15]

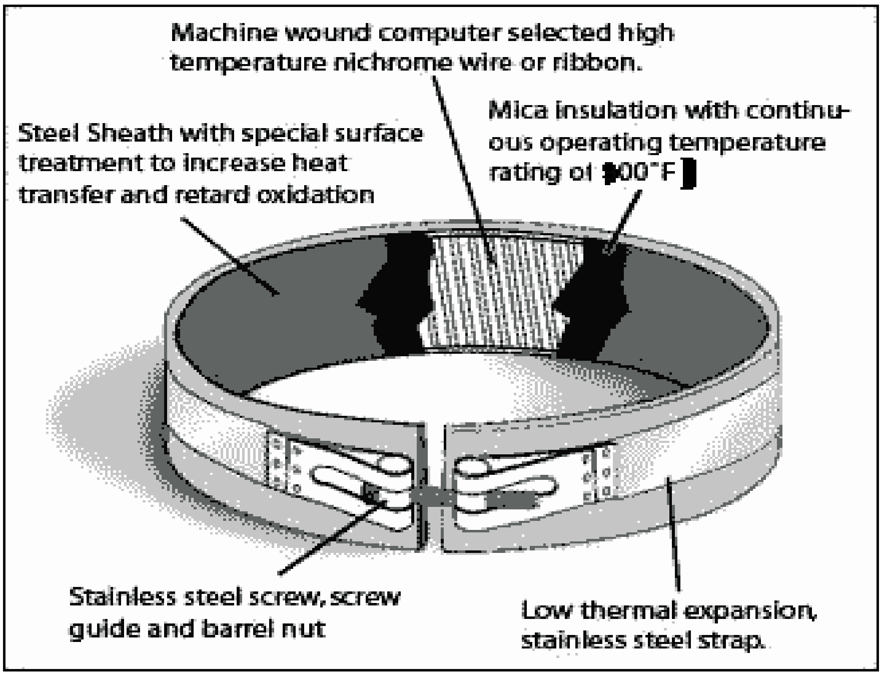


Figure 4. Standard mica band heaters. Google [15]

2.3.6 Cost

In a production line that has relatively long run, the cost of equipment includes its financial amortization, and could be about 5%. Plastic material cost could be as high 80% for high volume production. The other costs include power, water, labor, overhead and taxes. With precision, short run costs could be equipment as 20-30%, and materials at 45-50%. So, as it is usually stated, do not buy equipment just because it costs less, since more profit can occur with the more expensive equipment. Of course, the reverse is possibly true. So, buyer has to know what is wanted when ordering. A line with 1000-4000lb/h output would cost $0.5-1 million.

When you want to change a screw to see how your process is running, it seems expensive to take such action. Consequently, many people tend to run a poorly performing screw long after it should have been changed. Converting the cost of screw into an equivalent volume of plastic or into a profit per day will determine payback.
Rauwendaal [3]

Whenever possible, observing the following practices will help to reduce costs:

1. Strive for the simplest shape and form
2. Combine parts into single extrusions or use more than one die to extrude products/use multiple die heads and openings
3. Make gradual changes in thickness to reduce frozen stress
4. Where bends occur, use maximum permissible radii
5. Purchase plastic material as economical as possible and
6. Keep customers tolerance as liberal as possible, but once in production aim for tighter tolerances to save material costs and also probably reduce production costs.

2.3.7 Die land

A very important dimension is the length of the parallel die land. In general, it should be made as large as possible. However, the total resistance of the die should not be increased to the point where excessive power consumption and melt overheating occur. The required land length depends not only the type and temperature of the thermoplastic melt but also on the flow rate. The deformation of the melt in the entry section of the die invariably cause strain which only gradually decreases with time (relaxation). Usually the target is to allow the melt to relax before reaching the die. Otherwise the product dimensions and the mechanical properties may vary, particularly with rapid cooling. Rosato[4]

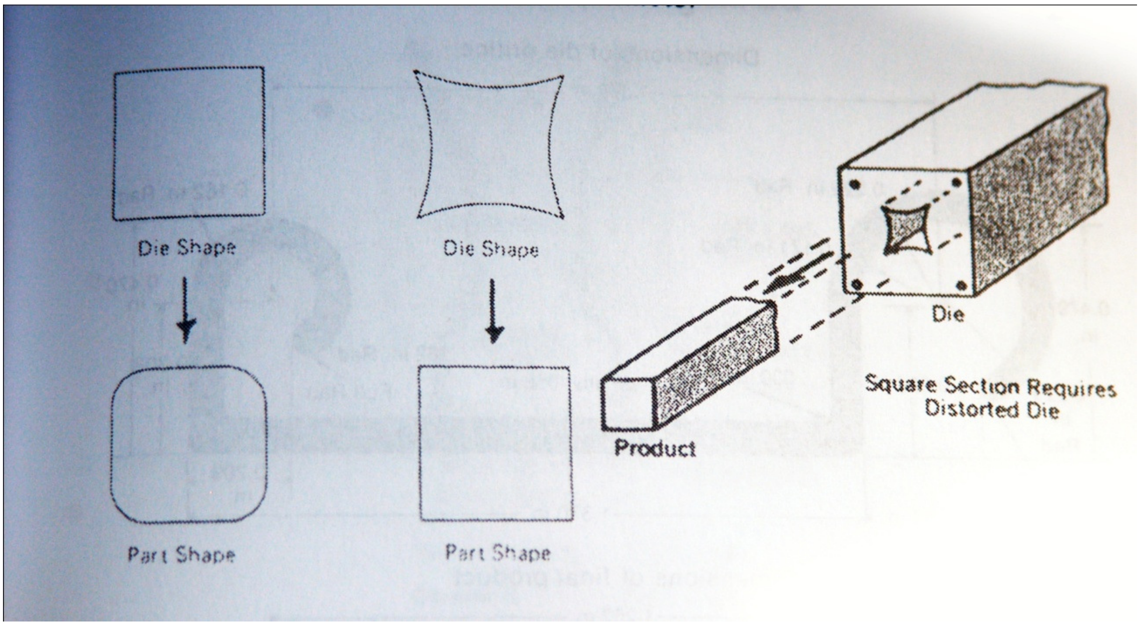


Figure 5. Effect of die orifice shape on a square extrudate. Rosato [4]

2.4 Polymeric Melt Behavior

2.4.1 Rheology

Rheology is the science of deformation and flow of materials. The Society of Rheology's Greek motto "Panta Rei" translates as "All things flow." Actually, all materials do flow, given sufficient time. What makes polymeric materials interesting in this context is the fact that their time constants for flow are of the same order of magnitude as their processing times for extrusion, injection molding and blow molding. In very short processing times, the polymer may behave as a solid, while in long processing times the material may behave as a fluid. This dual nature (fluid-solid) is referred to as Viscoelastic behavior. Ricardson [1]

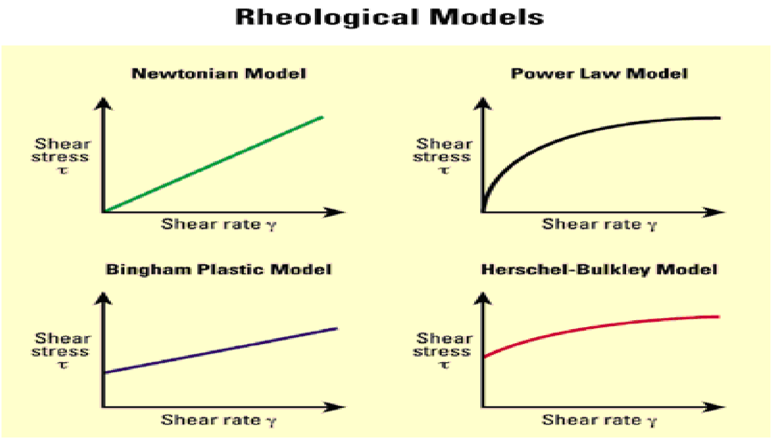


Figure 6. Rheological models [12]

Most polymer processes are dominated by the shear strain rate. Consequently, the viscosity used to characterize the fluid is based on shear deformation measurement devices. The rheological models that are used for these types of plows are usually termed Generalized Newtonian Fluids. In a Generalized Newtonian Fluids model, the stress in fluid is dependent on the second invariant of the stain rate tensor, which is approximated by the shear rate in most shear dominated flows. The temperature dependence of GNF fluids is generally included in the coefficients of the viscosity model. Various models are currently being used to represent the temperature and strain rate dependence of the viscosity. Ricardson [1]

2.4.2 Viscoelastic Fluid Behavior

This type of fluid behavior is characterized by the existence of yield stress which must be exceeded before the fluid will deform or flow. Conversely, such a material will deform elastically when the externally applied stress is smaller than the yield stress. Once the magnitude of the external stress has exceeded the value of the yield stress, the flow curve may be linear or non-linear but will now pass through origin. Hence in the absence of surface tension effects, such a material will not level out under gravity to form an absolutely flat free surface. Once can however, explain this kind of fluid behavior by postulation that the substance at rest consists of three- dimensional structures of sufficient rigidity to resist any external stress less than zero. For stress level greater than zero. However, the structure breaks down and the substance behaves like viscous material. In some cases, the buildup and breakdown of structure has been found to be reversible, i.e., the substance may regain its initial value of the yield stress. Richardson [1]

2.4.3 Non-Newtonian Fluid Behaviour

A non-Newtonian fluid is a one whose flow curve (shear stress versus shear rate) is non-linear or does not pass through the origin, i.e. where the apparent viscosity, shear stress divided by shear rate, is not constant at a given temperature and pressure but is dependent on flow conditions such as flow geometry, shear rate, etc. and sometimes even on the kinematic history of the fluid element under consideration. Such materials may be conveniently grouped into three general classes:

- Fluids for which the rate of shear at any point is determined only by the value of the shear stress at the point at that instant; these fluids are variously known as “time independent”, “purely viscous”, ”inelastic” or “generalized Newtonian fluids.
- More complex fluids for which the relation between shear stress and shear rate depends, in addition, upon the duration of shearing and there kinematic history; they are called “time dependent fluids. and finally,
- Substances exhibiting characteristics of both ideal fluids and elastic solids and showing partial elastic recovery, after deformation; these are categorized as “visco-elastic fluids”

This classification scheme is arbitrary in that most real materials often exhibit a combination of two or even all three types of non-Newtonian features. Generally, it is, however, possible to identify the dominant non-Newtonian charactertic and to take this as the basis for the subsequent process calculations. Also, as mentioned earlier, it is convenient to define an apparent viscosity of these materials as the ratio of shear stress to shear rate, though the latter ration is a function of the shear stress or shear rate and /or of time. Richardson [1]

2.4.4 Melt Behavior

An important approach to melt flow behavior is to recognize that the extruder and die operate as combined unit. The interaction between screw and die is usually represented by showing the dependence of the output on the melt pressure between and the screw and die head. The screw requires that the viscosity of the thermoplastic does not change either in the metering zone or in the die. This means that temperature and pressure changes and other influences on viscosity have to be avoided as much as possible. The pressure drop through a die varies directly with the land length and inversely with the cube of the gap opening. Richardson [1]

The non-Newtonian behavior of plastic makes its glow through a die somewhat complicated. When a melt is extruded from the die, there is usually some degree of welling. After exiting the die, it is usually stretched or drawn to a size equal to or smaller than the die opening. The dimensions are reduced proportionally so that, in an ideal plastic, the draw down section is the same as the original section but smaller proportionally in each dimension. The effects of melt elasticity mean that the plastic does not drawdown in a simple proportional manner; thus the drawdown process is source of errors in the profile. The errors are significantly reduced in a circular exturdate, such as pipe and wire coating .These errors are corrected by modifying the die and downstream equipment. Richardson [1]

Another important characteristic is that melts are affected by the orifice shape. The effect of the orifice is related to the melt condition and the die design with a slow cooling rate having a significant influence, especially in thick products. Cooling is more rapid at the corners; in fact, a hot center section could cause a product to blow outward and /or include visible or invisible vacuum bubbles. The popular coat-hanger die, used for flat sheet and other products, illustrates an important principle in die design. The melt at the edges of the sheet must travel further through the die than the melt that goes through the center of the sheet. A diagonal melt channel with a triangular dam in the center is a way of restricting the direct flow to some degree. Richardson [1]

2.4.5 Density

Plastics pellets, granules or beads vary in sizes and in densities. The table below shows the most common plastics with their respective densities and melting points.

Table 1. Density and melting points of some common plastics. Charles [16]

Material	**Density(g/cm^3)**	**Melting Point(^{o}C)**
Low density polyethylene	0.93	115
High density polyethylene	0.96	137
Polycarbonate	1.20	265
Polypropylene	0.90	175
Polyamide	1.14	265

When a plastic is extruded it's very crucial to understand when to use the bulk density and melt density values.

2.4.6 Melt Density

The melt density of neat polymer is an inherent property of the polymer and can be altered by fillers. “The melt density is measured as function of temperature at ambient pressure. The output rate of the polymer will be proportional to the melt density of the polymer”. Chung insists that “various polyethylene with different solid densities have the same melt density and the same compressibility. The melt density of a polyethylene at ambient pressure and 220C is 0.7432 g/cm^3” Chung [17]

2.4.7 Bulk Density

“the bulk density of a polymer is defined as the weight of the feed sample, example in the form of pellet, divided by the apparent volume of pellets or the container” According to Chung the bulk density depends on the size, geometry and distribution of pellets as well as the polymer properties.. Chung argues that the bulk density is directly proportional to the output rate per screw rpm and that the higher the bulk density the higher the output rate at a defined screw speed. “For a solid bed the bulk density increase with increasing pressure as the pellets are compressed “Chung [17]

2.5 Balance Equations

In extrusion, as well as in many other processes, one deals with the transport of mass, momentum and energy. Balance equations are used to describe the transport of these quantities. They are universal physical laws that apply to all media. A matter is considered as a continuum. Thus, the volume over which the balance equation is formulated must be larger enough to avoid discontinuities. Richardson[1]

2.5.1 Momentum Balance Equations

The momentum of a body is the product of its mass and velocity. Since velocity is a vector, momentum is also vector. The momentum balance equation describes the conservation of momentum; it is also referred to as the equation of motion.

Momentum can be transported by convection and conduction. Convection of momentum is due to the bulk flow of the fluid across the surface; associated with it is a momentum flux. Conduction of momentum is due to intermolecular forces on each side of the surface. The momentum flux associated with conductive momentum transport is the stress tensor. The general momentum balance equation is also referred to as Cauchy’s Equation. The Navier-Stokes equations are as special case of the general equation of motion for which the density and viscosity are constant. The well known Euler equation is again a special case of the general equation of motion; it applies to flow systems in which the viscous effects are negligible. Richardson[1]

2.5.2 Energy Balance Equations

The energy balance equation states that the rate of increase in specific internal (thermal) energy in a control volume equals the rate of energy addition by conduction plus the rate of energy dissipation. The principle of energy conservation is also described by the first law of thermodynamics.

The energy equation has to be used to analyze non-isothermal processes. In these situations, there are generally four unknown variables: velocity, stress, pressure, and temperature. In order to solve such a non-isothermal problem, one more equation is needed in addition to the three balance equations. The missing relationship is the constitutive equation of the fluid; this relationship basically describes the relationship between stress and deformation. In polymer extrusion the material undergoes large changes in temperature as it is transported along the extruder. Consequently, the energy equation is used extensively in the analysis of the extrusion process. Richardson[1]

2.5.3 Mass Balance Equations

The mass balance equation, also referred to as equation of continuity, is simply formulation of principles of the conservation of mass. The principle states that the rate of mass accumulation in control volume equals the mass flow rate into the control volume minus the mass flow rate out of the control volume. Richardson[1]

2.6 Flow Analysis

2.6.1 Drag Flow

Drag flow is flow caused by the relative motion of one or more boundaries with respect to the other boundaries that contain the fluid. It’s also referred to as Couette flow, although Couette flow is only a specific type of drag flow. Drag flow is important in extrusion. The two major boundaries that contain the polymer in the extruder are the barrel surface and the screw surface. Since the screw is rotating in a stationary barrel, one boundary is moving relative to the other; this causes drag flow to occur. Rauwendaal [3]

2.6.2 Pressure Flow

Flow caused by the presence of pressure gradients in the fluid; in other words local differences in the pressure. One of the most common examples of pressure flow (pressure driven flow) is the flow of water that occurs when one opens a water faucet. This flow occurs because the pressure upstream is higher than the pressure at the faucet. There is no relative motion of fluid boundaries (wall of the water pipe); thus, this pure pressure flow. In most extruder dies, the flow through is a pure pressure driven flow. The polymer melts flow through the die as a result of the fact that the pressure at the die inlet is higher than the pressure at the outlet. The flow rate is determined by the pressure at the die inlet, often referred to as die head pressure. Rauwendaal [3]

2.6.3 Shear Rate

The difference in velocity per unit normal distance (normal to the direction of flow). The rate of shearing or shear rate is one of the most important parameters in polymer melt processing. If the process is to be described qualitatively, the shear rate in the fluid at any location needs to be known. Rauwendaal [3]

Shear rate, $\gamma = \frac{6\,Q}{W\,H^2}$, (2.3)

2.6.4 Shear Strain

Displacement (in the direction of flow) per unit normal distance over a certain time period. The units of shear rate are s-1 and the shear strain is dimensionless number. Rauwendaal [3]

2.6.5 Shear Stress

The stress required to achieve a shearing type of deformation. Which a fluid is sheared, a certain force will be required to bring about the deformation. This force divided by the area over which it works is the shear stress. Rauwendaal [3]

2.7 Flow Models

2.7.1 Newtonian and non-Newtonian Fluids

The concepts of Newtonian and non-Newtonian fluids can be well acknowledged when viscosity is explained. The viscosities of some fluids depend on shear rates whilst others are not. It may be recalled that the viscosity of fluid is result of internal friction of fluid molecules.

2.7.2 Newtonian Fluids

Fluids with constant viscosity at constant temperature independent of shear rate are Newtonian fluids; example is water. The figure below shows how fluids are characterized as Newtonian and non-Newtonian in relation with shear.

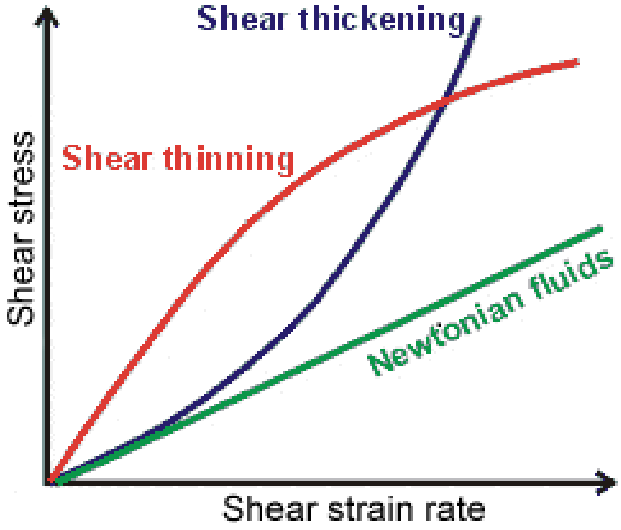


Figure 7. Newtonian Fluids Google [13]

2.7.3 Non-Newtonian Fluids

The viscosity of polymer melt (complex fluids) at a constant temperature depends on shear rate. The structures of the fluid change with shear rate. A fluid that has its viscosity depending on a shear rate at constant temperature is called a non-Newtonian fluid (Chung, 2000). There are two types of non-Newtonian fluids. These are dilatants and pseduoplastics. "The viscosity of the dilatants fluid increase with shear" and "the viscosity of the pseduoplastics fluid decrease with shear" (Chung, 2000, p.102). The pseduoplastics are shear thinning fluids whilst the dilatants are the shear thickening fluids. Polydynamics [9]

2.7.4 Power Law Model

“The power law model is one of the simplest models for presenting the viscous-shear behavior of plastic melt. The law accurately demonstrate the shear thinning region in the viscosity versus strain rate curve”. The proponents of the law suggested the relationship between viscosity and shear rate as follows:

$$\eta = m(T^{o}C)\gamma^{n-1} \tag{2.4}$$

Where m = consistency index

n = power law index

[Osswald, (11, P.137)]

Table 2. Power law parameters for some common plastics. Charles [16]

Polymer	$m(Pa\text{-}s)^n$	n	T(°C)
High density PE	2.00×10^4	0.41	180
Low density PE	6.00×10^3	0.39	160
PP	7.5 0x 10^3	0.38	200
PA 66	6.00×10^2	0.66	300
PC	6.00×10^2	0.98	300

The power law is usually represented as $\eta = m \gamma^{n-1}$, where m is sometimes replaced by 'k' or other letter (Michaeli, 2003, p.22). The consistency index is said to include the temperature dependence of the viscosity whilst the power law index represents the shear thinning behavior of the polymer melt. "The limits of the law are zero (0) and infinity" Osswald [11]

η approaches 0 when shear rate goes into infinity and η approaches infinity as shear rate becomes very infinitesimal.

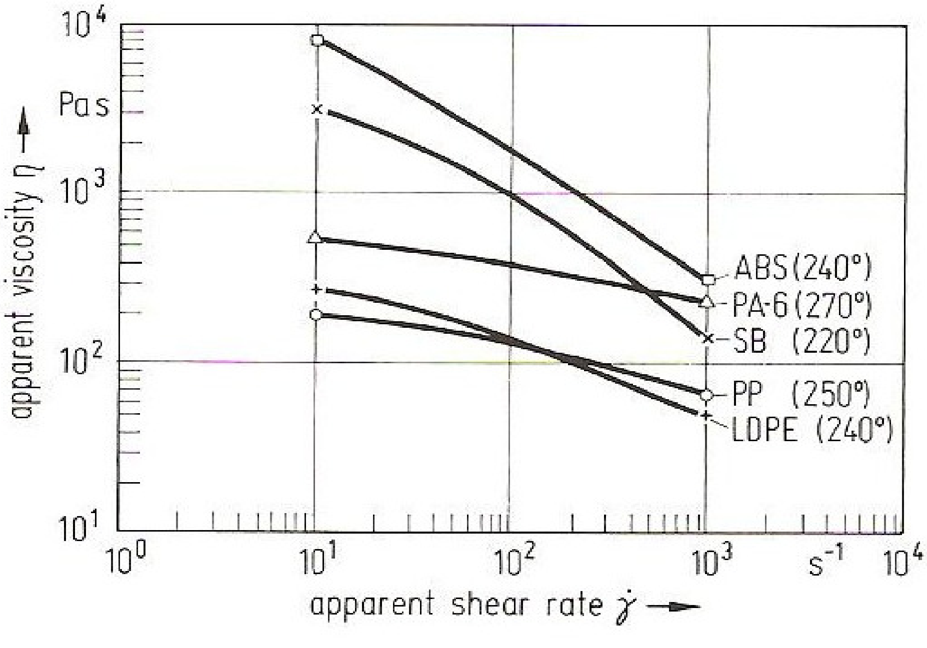


Figure 8. Viscosity - Shear rate curve for some common plastics

2.7.5 Drag and Pressure flows

Once the extrusion process is started, it is important to know how much material is fed into the system and how much is extruded out, for example in a given time interval and a screw rpm. According to Eric A Grulke the flow process occurs in tow phases. These phases are drag and pressure phases. The flow due to the internal friction between the malt pool and the barrel walls and the shear action of the screw constitutes the drag flow [Eric Grulke, p.553]

The pressure flow of a fluid is cause by a pressure difference. “The pressure drop is linear in direction of flow in channels with parallel walls. In the metering section an extruder screw, pressure flow is the relatively backward flow of material down the screw channel caused by pressure in the head” Polydynamics [9]

2.7.6 Flow analysis

The pressure distribution of the flow in the extruder is the total output obtained from the drag flow, back pressure flow and leakage. Assuming that there is no leakage. The extruder and die characteristics graph can be extracted.

$$Q = \frac{1}{2}\pi^2 D^2 NH \sin\emptyset \cos\emptyset - \frac{\pi D H^3 \sin^2\emptyset}{12\eta}\frac{P}{L} = Q_d - Q_p$$

Where

Q_d – Drag flow (m^3/s)
Q_p – Pressure flow
D – Diameter of the screw (m)
N – Screw revolution (rpm)
H – Channel depth of the screw (m)
$\emptyset$ – Helix angle of screw
L – Length of the screw (m)
P – Operation pressure (Pa)
η –Viscosity (Pa.s)
(Crawford, 1998. P.256)

When there is no pressure build up at the end of the extruder, any flow is due to drag and maximum flow rate Q_{max} can be obtained. The equation then can be reduced to only the drag term as follows.

$$Q = Q_{max} = \frac{1}{2}\pi^2 D^2 NH \sin\emptyset cos\emptyset \qquad (2.5)$$

Similarly, when there is a high pressure drop at the end of the extruder the output of the extruder, Q becomes equal to zero (Q=0) and the maximum pressure is obtained from the equation.

$$\frac{1}{2}\pi^2 D^2 NH \sin\emptyset cos\emptyset = \frac{\pi D H^3 sin^2\emptyset}{12\eta}\frac{P}{L}$$

$$\text{Hence } P = P_{max} = \frac{6\pi DLN\eta}{H^2 tan\emptyset} \qquad (2.6)$$

(Crawford, 1998, p.257)

3 METHOD

3.1 Die Modeling

Based on the theoretical framework an extrusion die has been modeled using Solid Edge ST software. The design is made for a rectangular profile that has dimension of 8mm X 3mm.

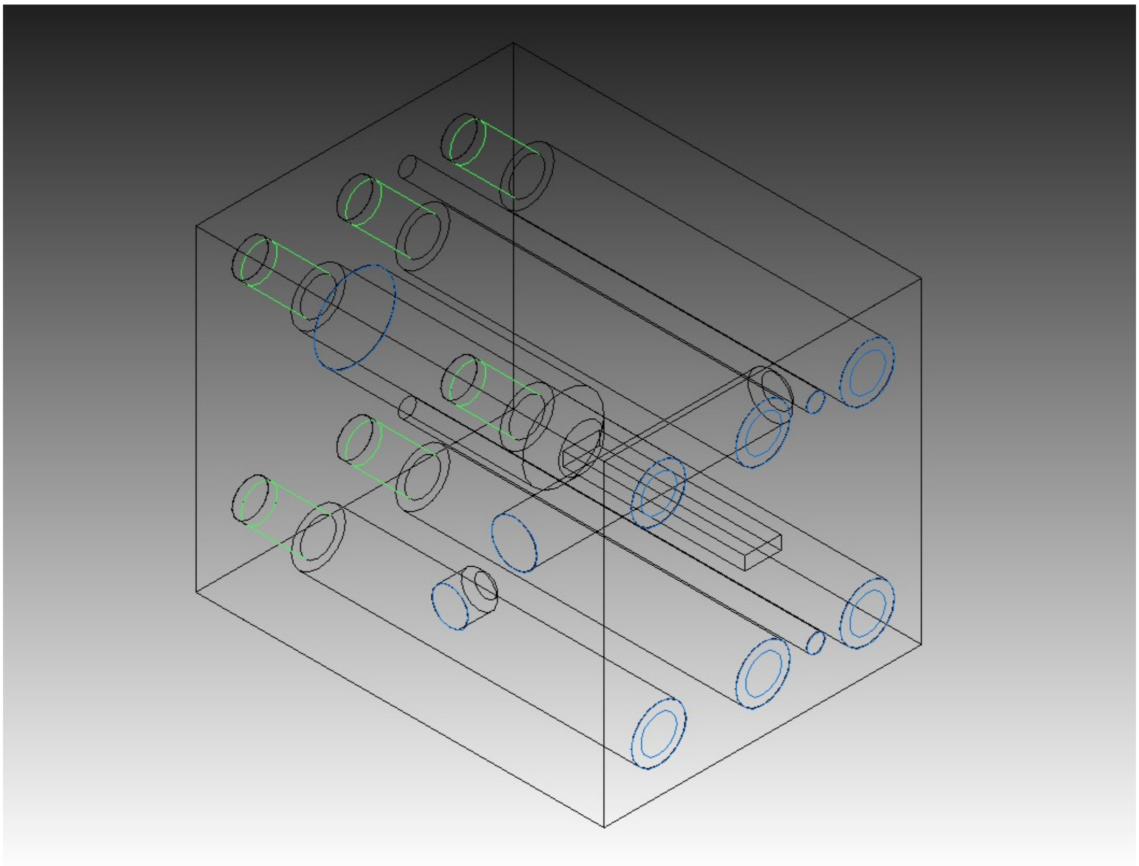


Figure 9. Solid Edge modeling of the Die

The whole die body has a dimension of 90mm*70mm*70mm. In order to minimize the amount of die swell the die land has to be long as much as possible. Therefore the die length has been given a size of 40mm. The metric draft of the die is shown below in Figure.

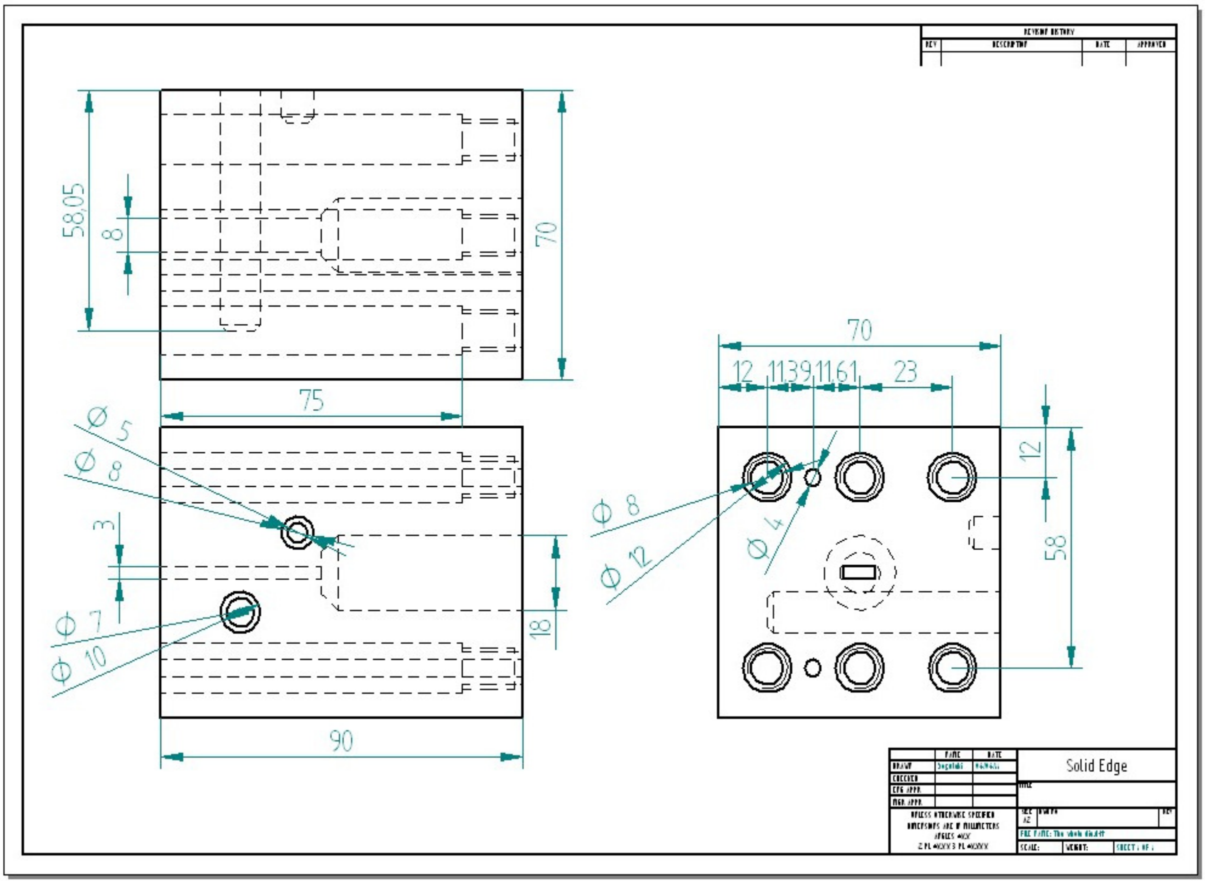


Figure 10. Metric Draft of the Die

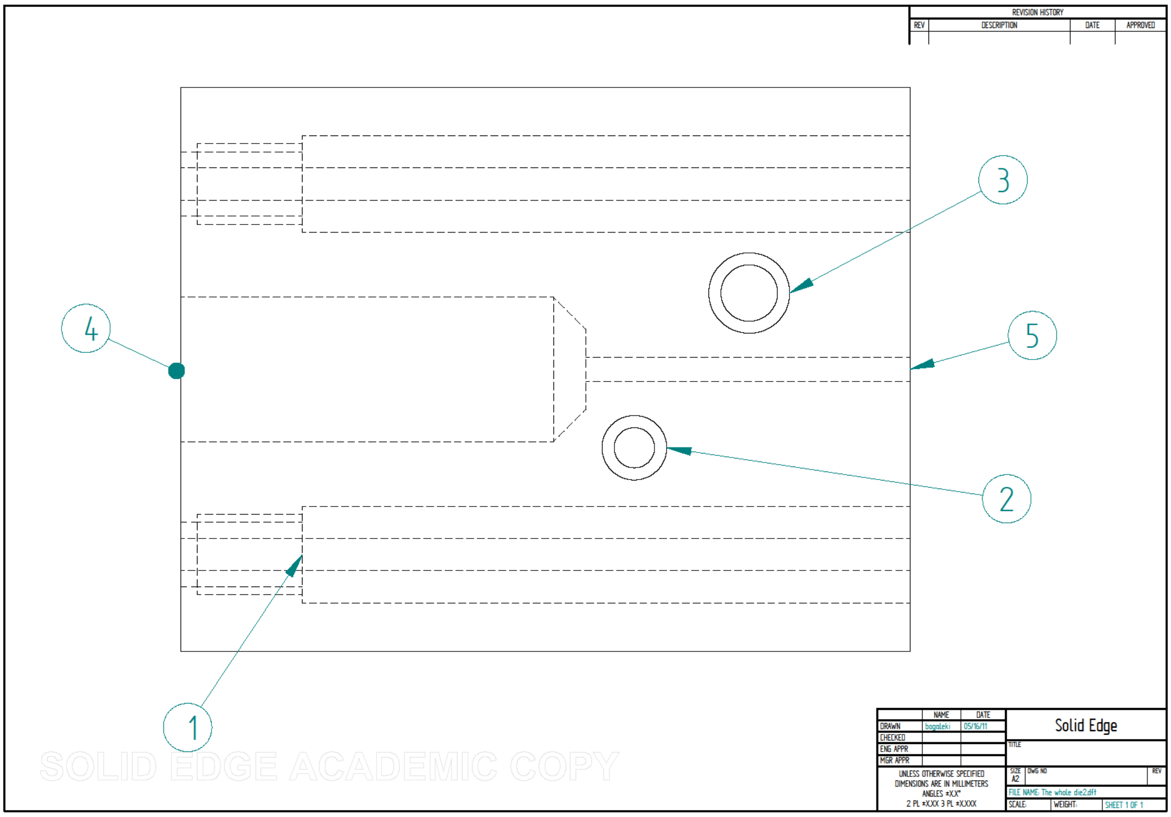


Figure11. Die detailed drawing

1. Bolts
2. Heat sensor
3. Heating element
4. Die inlet
5. Die outlet

3.2 Extruder line calculation

From equation (2.5) and (2.6) the point for the extruder line can be obtained. Based on the above information the maximum flow rate has been calculated for the screw parameter of D = 0.175m, $\emptyset$ = 14.5° , N = 30rpm L= 0.64m and H = 0.004m at P = 0.

$$Q_{max} = \frac{1}{2}\pi^2(0.175m)^2(\frac{30}{60}s)(0.004) \sin 14.5° \cos 14.5°$$

$$= 7.33 \text{ X } 10^{-7} \text{ m}^3/\text{s}$$

Similarly, P_{max} can be determined when Q = 0

$$P_{max} = \frac{6\pi DLN\eta}{H^2 tan\emptyset}$$

Viscosity, η = m γ^{n-1} where n = 0.39 as shown in Table 2

Shear rate for a quadratic cross section is given by $\gamma = \frac{6\,Q}{W\,H^2}$,

Where W = width and H = height of the rectangular channel that the melt flows through. In this case Q is the experimental flow rate through the channel, in order to be able to get the shear rate or viscosity. Using formula (2.3) the shear rate can be extracted as follow.

$$= \frac{6\,(7.33*10^{-7})}{(0.008)*(0.003)^2}$$

$$= 61.1 s^{-1}$$

Therefore

$$\eta = m\,\gamma^{n-1}$$

$$= (6*10^{3}\ \text{Pa.s})\ (61.1\text{s}^{-1})^{0.39-1}$$

$$= 488.35\ \text{Pa.s}$$

Based on the viscosity-shear rate curve this value is too high. Since the maximum viscosity for LDPE at 240°C is 300 Pa.s. The shear rate value of 61.1s^{-1} corresponds to approximately 200 Pa.s.

$$P_{max} = \frac{6\pi DLN\eta}{H^{2}tan\emptyset}$$

$$= \frac{6*\pi*(0.0175m)(0.64m)\left(\frac{30}{60s}\right)(200Pa.s)}{(0.004m)^{2}tan14.5}$$

$$= 5.1\text{MPa} \quad \text{When } Q = 0$$

This is the maximum pressure obtained when the flow rate is minimum.

3.3 Die characteristic for rectangular channel

The die characteristic for a rectangular profile can be calculated using formula (2.1)

$$Q = \left(\frac{(0.78)\mathrm{x}(0.008\mathrm{m})\mathrm{x}(0.003\mathrm{m})^3}{12(200Pa.s)0.09}\right) \mathrm{X}\ 5.1\mathrm{x}10^6\mathrm{MPa}$$

$$= 3.96\ \mathrm{X}\ 10^{-6}\ \mathrm{m}^3/\mathrm{s}$$

And the operating pressure is obtained from

$$P_{op} = \left\{\frac{2*\pi*(200Pa.s)(0.0175m)^2\left(\frac{30}{60s}\right)(0.004m)sin14.5cos14.5}{\frac{(0.78)(0.008m)(0.003m)^3}{3*\pi*0.09}+\left(\frac{(0.0175m)(0.004m)^3\sin^2 14.5}{3(0.09)}\right)}\right\}$$

$$= 0.41\mathrm{MPa}$$

$$Q_{op} = K*P_{op}$$

Where $K = Fbd^3/12L_d$

$$Q_{op} = \left\{\frac{(0.78)(0.008)(0.003)^3}{12(200Pa.s)0.09}\right\} \mathrm{X}\ 0.41\mathrm{MPa}$$

$$= 3.18 * 10^{-7}\mathrm{m}^3/\mathrm{s}$$

Table 3. Extruder operating points

	Q x 10^{-7}(m^3/s)	P X 10^{6}(Pa)	$\dot{m}$(kg/hr)
Extruder	7.33	0	1.96
	0	5.1	0
Die	0	0	0
	39.7	5.1	10.5
Operating point	3.18	0.41	

3.4 Subdomain settings

The designed die has been analyzed on COMSOL multi physics using the following parameters.

Table 4 Subdomain settings for LDPE. Charles [16]

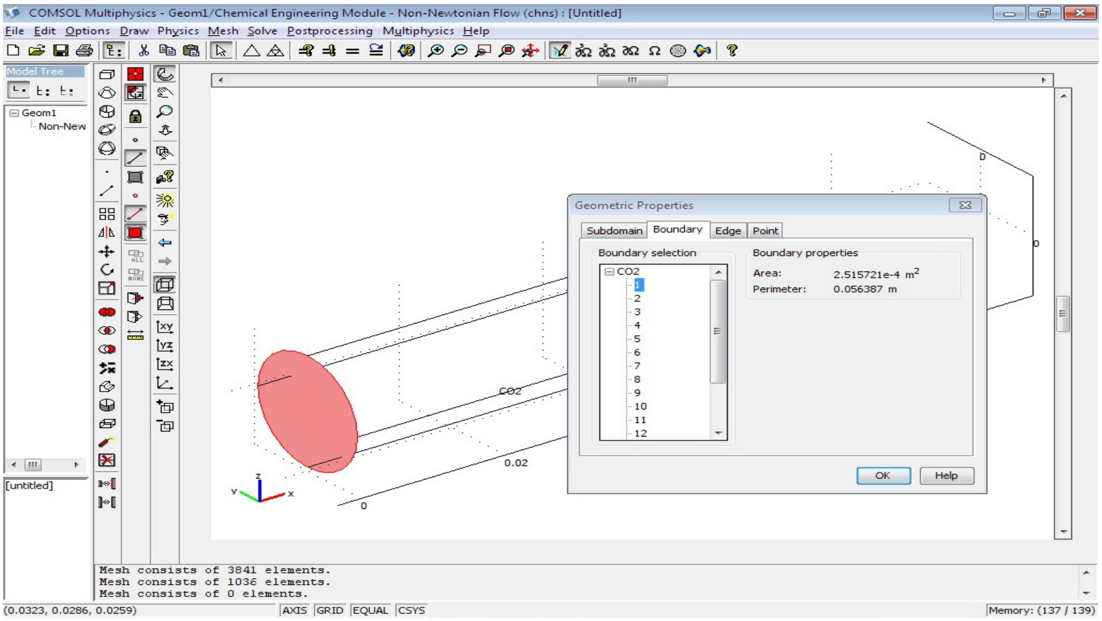
Viscosity model type	**Carreau model**
Density of melt LDPE(rho)	743 kg/m^3
Zero shear rate viscosity	1437.4Pa.s
Model parameter(n)	0.39
Model parameter(λ)	0.015s

The initial velocity value of the polymer was calculated based on the maximum extrusion output.

$$Q_{max} = \frac{1}{2}\pi^2(0.175m)^2(\frac{30}{60}s)(0.004)\ \sin 14.5° \ cos 14.5°$$
$$= 7.33 \text{ X } 10^{-7}\ m^3/s$$

But since the software doesn’t understand the unit we have to convert it into velocity by dividing it by the inlet area.

The exact area of the inlet and the outlet of the die were extracted from the Comsol multi physics software. Using the software it was possible to obtain the accurate areas using the Geometric properties option.



Boundary selection: CO2 — 1 (selected), 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12

Boundary properties

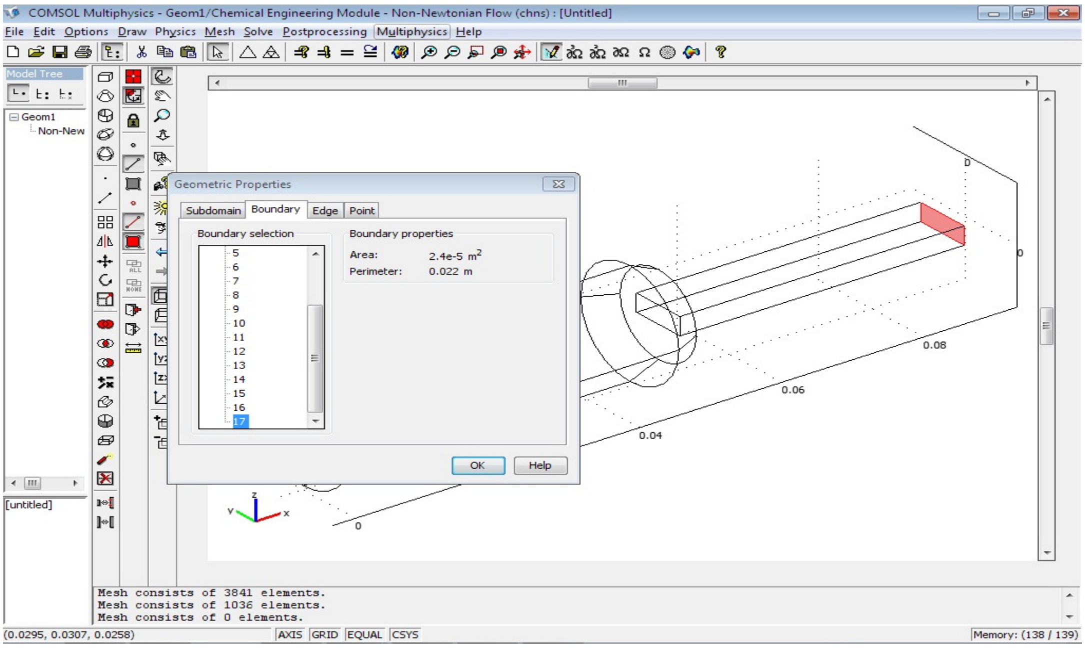
Area: 2.515721e-4 m^2
Perimeter: 0.056387 m

```
Mesh consists of 3841 elements.
Mesh consists of 1036 elements.
Mesh consists of 0 elements.
```

(0.0323, 0.0286, 0.0259)

Memory: (137 / 139)

Figure 12. Die inlet area



Boundary selection: 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17 (selected)

Boundary properties

Area: 2.4e-5 m^2
Perimeter: 0.022 m

```
Mesh consists of 3841 elements.
Mesh consists of 1036 elements.
Mesh consists of 0 elements.
```

(0.0295, 0.0307, 0.0258)

Memory: (138 / 139)

Figure 13. Die outlet area

The next step would be to figure out the velocity drop at the inlet of the die. This can be calculated using the drag flow, which is maximum at the end of the extruder (at the entrance of the die) and the entrance area of the Die.

$$Q = \text{Velocity} * \text{Area}_{in}$$

$$V = Q / A$$

$$= 7.33 \text{ X } 10^{-7} \text{ m}^3/\text{s} / 2.51 \text{ X } 10^{-4} \text{ m}^2$$

$$= 2.92 \text{ X } 10^{-3} \text{ m/s}$$

Once the velocity is obtained, the next thing would be to analyze the die on Comsol software to get the suitable pressure that corresponds to the velocity.

4 RESULTS

4.1 Post processing

Here the mass flow rate of the die was analyzed at a pressure value of 0.41 MPa. This is the calculated operating pressure. The velocity field obtained at the center of the rectangular section of the die is as follow.

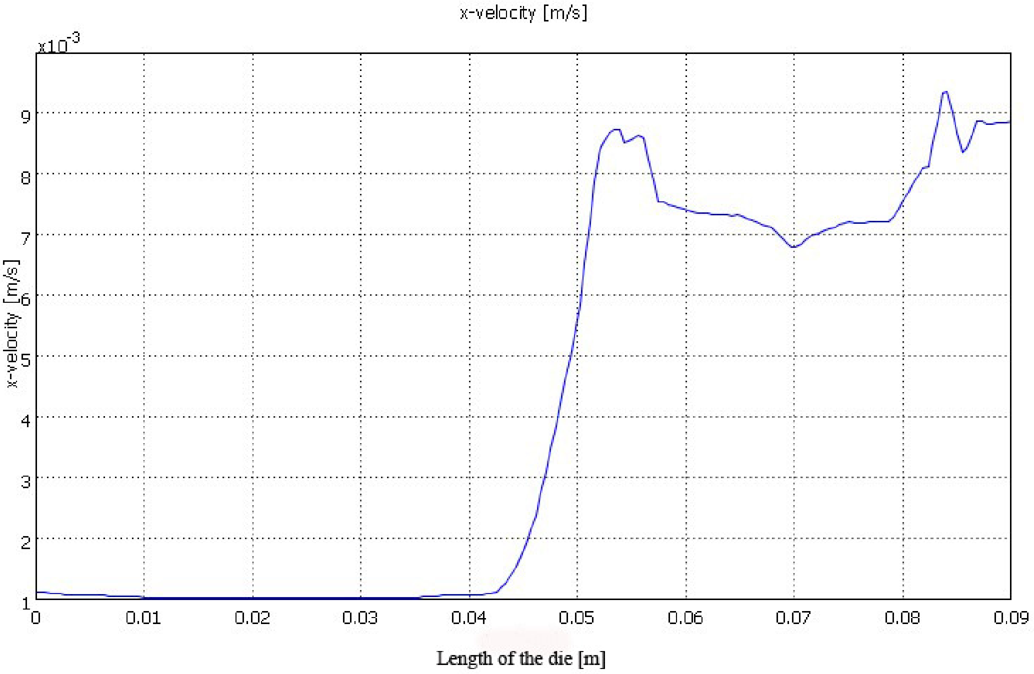


Figure 14 Velocity curve at 0.41MPa

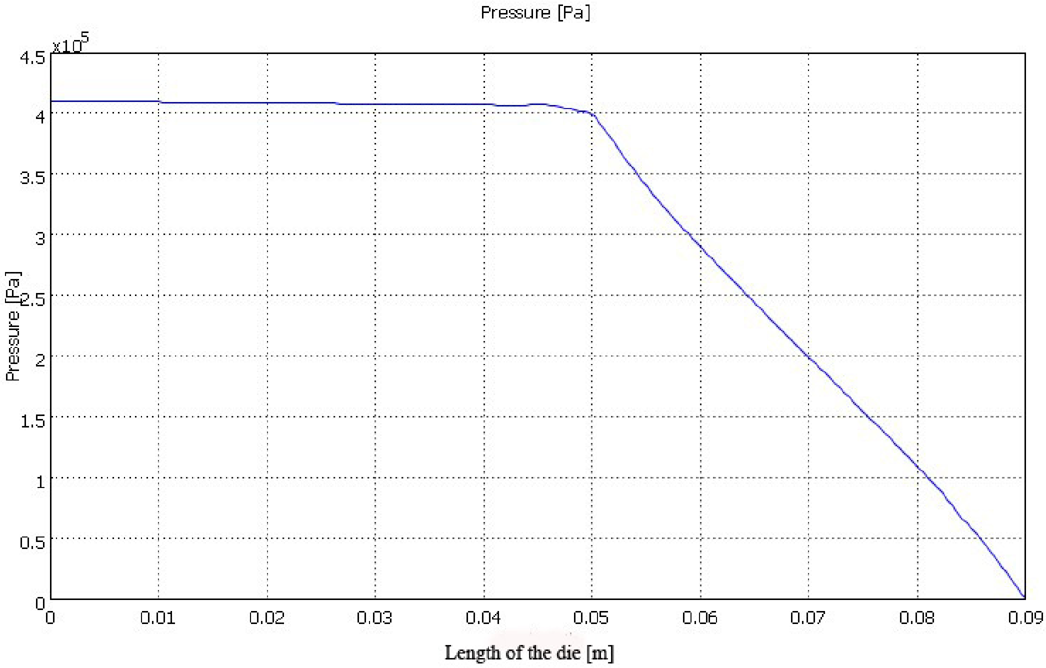


Figure 15 Pressure curve

From this graph we can conclude that the pressure at the end of the extrudate is always going down to zero. Since the objective is to find the mass flow rate at the pressure of 0.41MPa.

The min value of the velocity can be calculated by zooming in the x=0 value until similar value is obtained. The obtained result was 2.8974*10^{-3}m/s. Since the maximum value changes it's not possible to use the above method to obtain the max value. Therefore we can use the plot parameter to obtain the max value.

Using Figure 14 the average velocity of the die can be obtained at 0.41MPa.

$$V_{av} = V_{max} / 2$$

$$= (8.86 * 10^{-3} \text{ m/s}) / 2$$

$$= 4.43 * 10^{-3} \text{ m/s}$$

Area of the outlet surface would be 2.4*10^{-5} as shown in figure 10.

Therefore

Mass flow rate, $\dot{m} = \rho \upsilon A$

$$= 743\text{kg/m}^3 * 4.43*10^{-3} \text{ m/s}* 2.4*10^{-5}\text{m}^2$$

$$= 7.89*10^{-5} \text{ kg/s}$$

To change it into kilogram per hour it's multiplied by 3600s

$$= 7.89*10^{-5} \text{ kg/s x 3600s}$$

$$= 0.28 \text{ kg/hr}$$

There fore the mass flow rate is 0.28kg/hr.

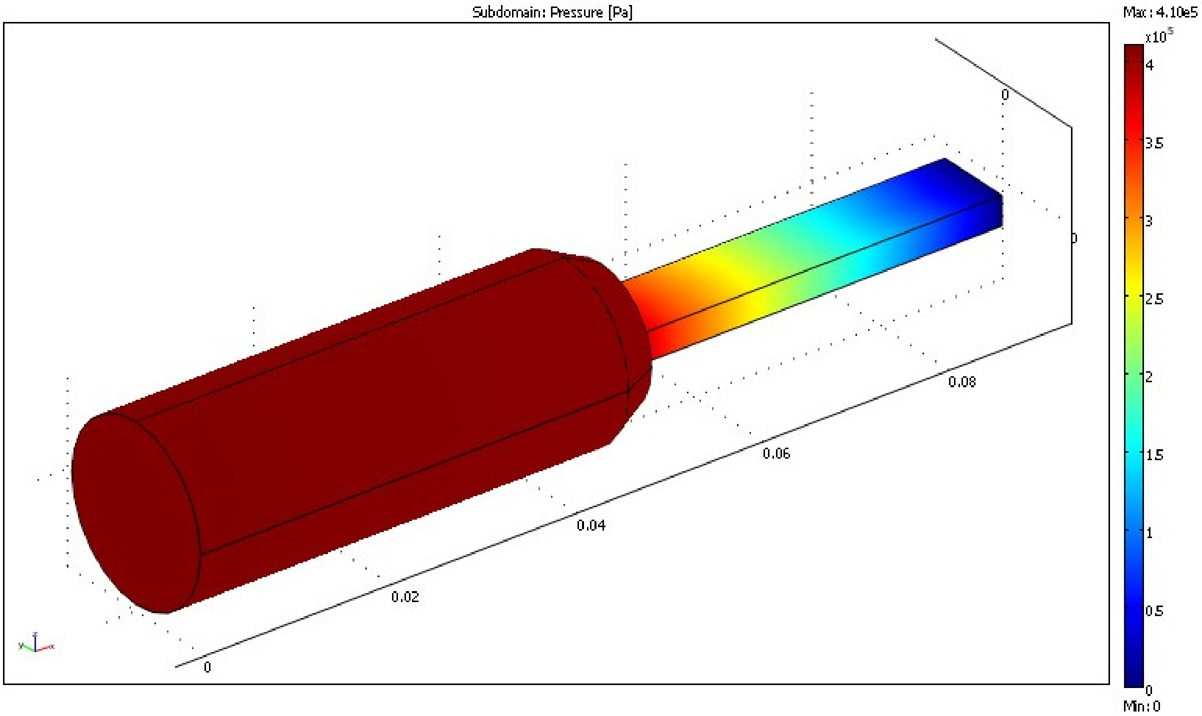


Figure 16. Pressure distribution in the die at 0.41MPa

Inorder to maintain a uniform flow, the ratios of inlet velocity to the outlet velocity has to be equal to the ratio of the outlet area to the inlet area in the direction of flow. Calculating the area ration from Figure 12 and 13 gives a value of 0.1.

The ratio of the velocites is

$$V_{in}/V_{out} = 1.13*10^{-3}/8.86*10^{-3} = 0.12$$

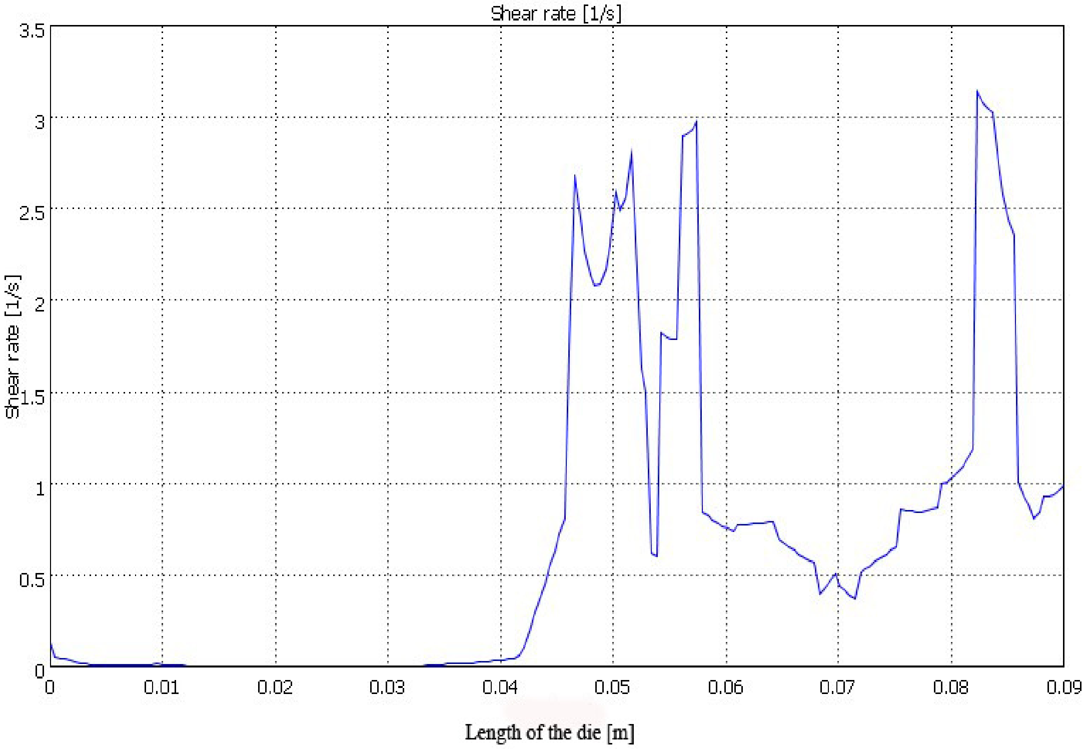


Figure 17. Shear rate curve at 0.41MPa

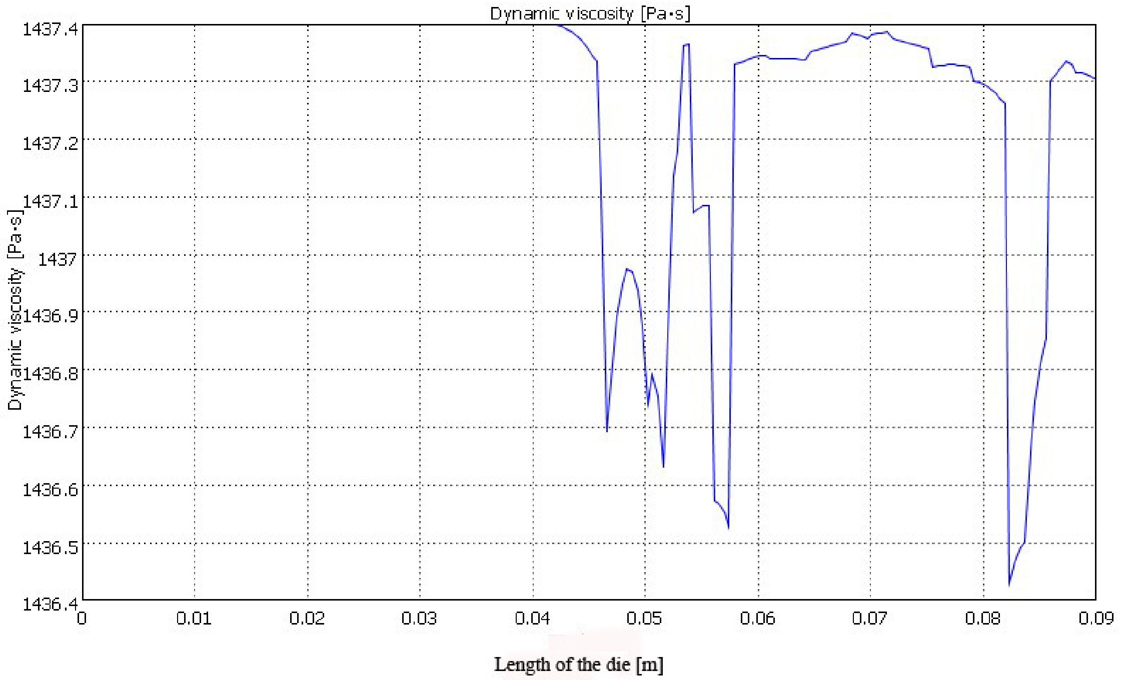


Figure 18. Dynamic Viscosity Curve

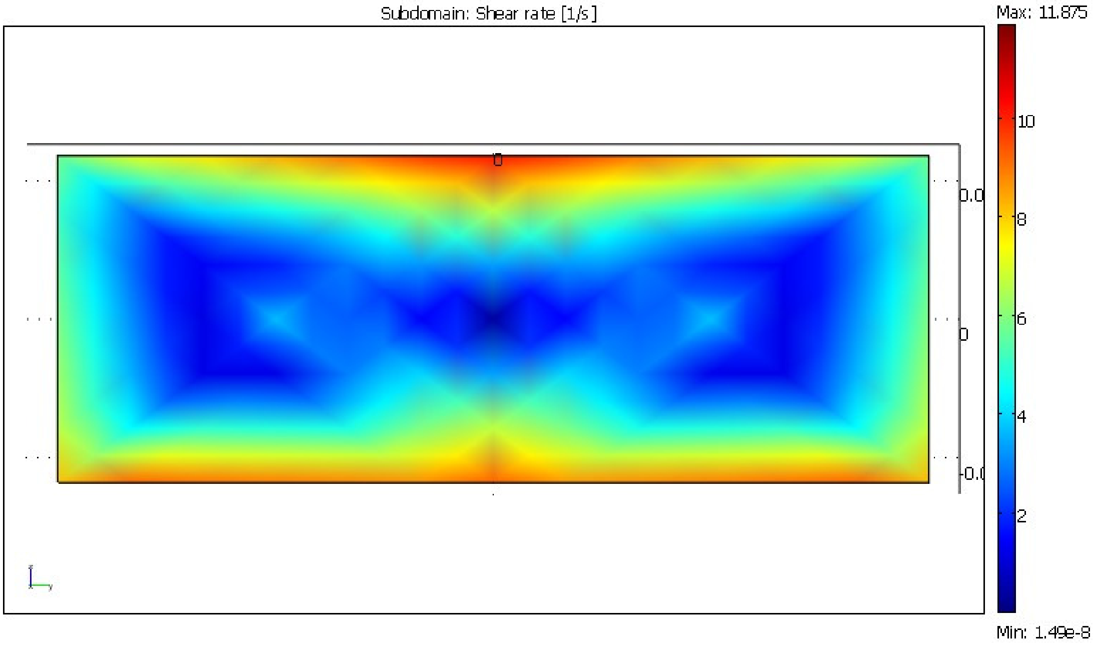


Figure 19. Uneven stress distribution at the corners

As shown in the above image the stress at the corners of the rectangular section is not even. This causes the extrudate to swell and comes out with oval shape. This can be solved by optimizing the die geometry and trying to even the stresses at the corners.

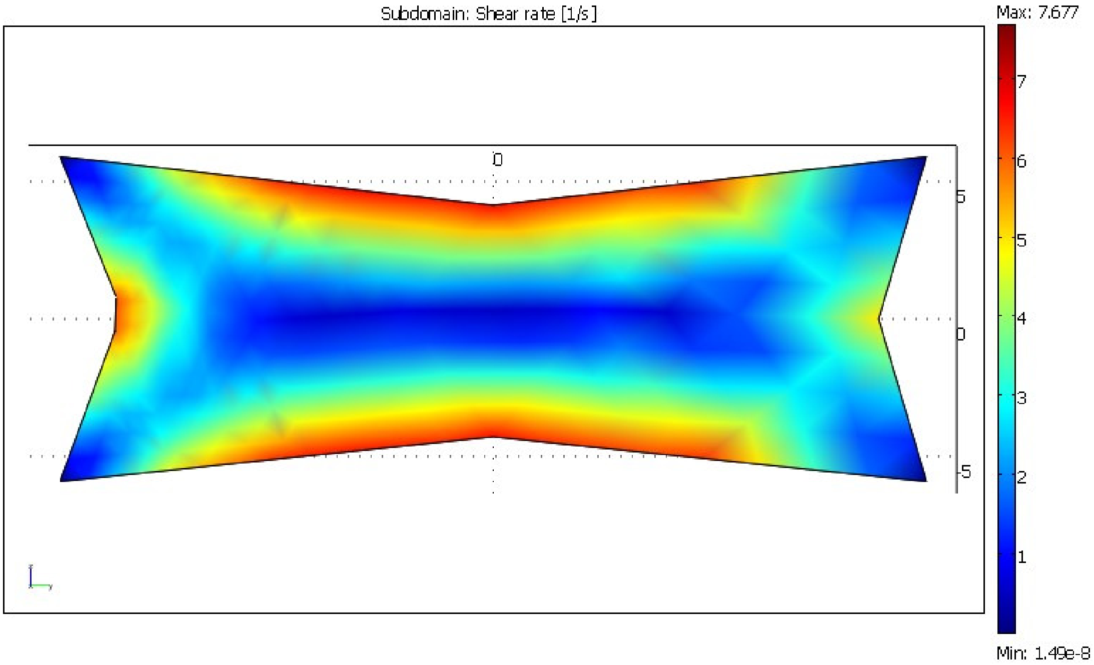


Figure 20. Optimized die geometry

In Figure 20 the die shape has been optimized in order to get nearly similar stresses at the corners of the die.

5 CONCLUSION

In this thesis work a die with rectangular orifice has been modeled and simulated on computer software. The operating pressure was calculated and mass flow rate was obtained.

The Carreau model was used to analyze the die on COMSOL multi physics software and the die was designed for a LDPE plastic material at around 220 degree centigrade.

Based on the extruder's screw parameter the flow rate in the extruder was calculated. This helps to obtain the pressure in the extruder. That is, when the pressure is at its minimum there will be maximum output and when the volume flow rate is at its minimum there will be maximum pressure.

Even though the die has been optimized in order to get similar shear stress distributions across the die. It was not possible to simulate the exact dimensions of the die for a rectangular profile with Comsol.

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APPENDIX

Absolute Viscosity – a term used interchangeably with viscosity to distinguish it form either kinematic viscosity or commercial viscosity. Absolute viscosity is the ratio of shear stress to shear rate. IT is a fluid's internal resistance to flow. The common unit of absolute viscosity is the poise. Absolute viscosity divided by fluid density equals kinematic viscosity. It is occasionally referred to as dynamic viscosity. Absolute viscosity and kinematic viscosity are expressed in fundamental units.

Apparent Viscosity – The ratio of shear stress to rate of shear of a non-Newtonian fluid such as lubricating grease, or multi-grade oil, calculated from Poiseuille's equation and measured in poises. The apparent viscosity changed with changing rates of shear and temperature and must, therefore, be reported as the value at a given shear rate ad temperature

Back Pressure – The resistivity of molten plastic material to forward flow.

Barrel – The part of the extruder encasing the screw or plunger.

Barrel Liner – The sleeve forming the inner surface of the barrel.

Calendaring – The process of pressing or smoothing material between rollers.

Cladding - also known as "sidings" is the extruder PVC-U boards that are used as outdoor weather-resistant façade panels

Compound – Any plastic material prepared for subsequent manufacturing processes, specifically extrusion, molding or calendaring.

Compression Section – The transition section of screw channel in which a reduction in the screw channels volume occurs.

Die – The component on a plastics extruder affixed to the extruder head through which the melt is pushed to form the desired profile.

Die Plate – In moulds, the main support for the punch or mould cavity.

Dry Blend – A free flowing blend of compound or resin and other ingredients are prepared for an additional manufacturing operation specifically for extrusion or molding.

Extrudate – The product or result of an extrusion process. An extrudate is a product or material forced though a shaping orifice as continuous body.

Extruder Size - The minimal inner diameter of the extruder barrel

Extrusion Coating – A coating technique in which molten plastic feeds directly from an extruder die into a nip-roll assembly combined with the substrate.

Heat Aging – The unique process of aging a thermoplastic or thermoset product and examining the percentage of retained physical and chemical properties after exposure to heat for prolonged period of time.

Melt – Any extrusion material heated to plastics condition.

Melt strength – A term that refers to the strength of molten plastic.

Outer Die Ring – The element of tubing tie that shapers the outer surface of a tube.

Pellets – Resins or mixtures for resins with compounding additives in the shape of similar sized tables and granules that have been extruded or chopped into short segments to prepare them for molding operations.

Ram Extruder – A barrel with temperature control, where in a plunger pushes material in a melted state to the Die.