SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

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FINITE VOLUME SIMULATION OF FLOW OF POLYMER IN AN EXTRUSION DIE

By

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DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled **"FINITE VOLUME SIMULATION OF FLOW OF POLYMER IN AN EXTRUSION DIE".** I also declare that it has not been previously submitted for the award of any degree or diploma or the similar title of this for any other examining body or university.

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LIST OF ABBREVIATIONS

LDPE	Low Density Polyethylene
PLA	Polylactic Acid
Tg	Glass Temperature
Mw	Molecular Weight
B	Die Swell Ratio
SCF	Stress Concentration Factor
FEM	Finite Element Method
CAD	Computer-aided design
3D	Three Dimensional
SMPs	Shape-Memory of Polymers

NOMENCLATURES

η_0	Zero Shear Viscosity
η	Viscosity
η_∞	Infinite Shear Viscosity
C	Mass Concentration Fraction
λ	Lambda
ρ	Density
γ	Apparent Viscosity
τ	Torque
λ_c	Time Constant
n	Power-Law Index
K	Thermal Conductivity
τ^*	Power Law Region

ABSTRAK

SIMULASI ISIPADU TERHINGGA ALIRAN POLIMER DALAM DAI PENGEKSTRUDAN

Reologi adalah tingkah laku aliran polimer. Tujuan kajian ini adalah untuk mengkaji dan memahami tingkah laku aliran Low Density Polyethylene (LDPE) melalui acuan pengekstrudan. Pengekstrudan skru tunggal dalam tiga dimensi(3D) telah digunakan. Dalam simulasi ini, FLUENT 15.0 telah digunakan untuk mengesahkan model kelikatan (Model Cross). Kesan proses parameter ke atas tingkah laku pembengkakan dai telah dikaji. Simulasi telah dijalankan pada suhu dan tekanan yang berbeza. Kajian mendapati bahawa semakin tinggi suhu semakin rendah nisbah pembengkakan dai. Kajian juga menunjukkan peningkatan dalam tekanan akan meningkatkan pembengkakan dai. Terdapat beberapa kesan ke atas pembengkakan dai yang dipengaruhi oleh berat molekul polimer. Ini dapat diperhatikan dengan membandingkan LDPE dan Polylactic Acid (PLA). LDPE menunjukkan nisbah pembengkakan dai lebih rendah. Kesan parameter proses seperti suhu, kelajuan skru dan tekanan ke atas reologi telah dikaji dalam kajian ini. Parameter proses memberi kesan kepada kelikatan leburan LDPE. Selain itu, corak aliran mendapati cairan polimer menjadi lurus apabila mengalir ke arah dai. Untuk menjalankan kajian dalam simulasi aliran polimer, pelbagai parameter perlu diambil kira. Kekuatan FLUENT 15.0 dalam mengendalikan simulasi proses pengekstrudan memerlukan kajian yang lebih teliti supaya keputusan yang diperolehi lebih tepat dan berkesan.

ABSTRACT

FINITE VOLUME SIMULATION OF FLOW OF POLYMER IN AN EXTRUSION DIE

Rheology is the behavior of flow of polymer. The aim of the study was to observed and understands the behavior of the flow of Low Density Polyethylene (LDPE) through an extrusion die. Three dimensional (3D) simulation of polymer rheology in an single screw extrusion was used. In this simulation, the FLUENT 15.0 software was used to verify the viscosity model (Cross model). This study was determined the effect of process parameter on die swell behavior. Simulation was carried out on the different temperature and pressure. The higher the temperature result in decreasing the die swell ratio. The effect of pressure shows increasing the pressure will increase the die swell ratio. There was some effect on the die swell that influenced by molecular weight of the polymer. This was observed by comparing Low Density Polyethylene with Polylactic Acid (PLA). LDPE shows to have lower die swell ratio. The affect in process parameters such as temperature, screw speed and pressure on its rheology were studied. The process parameters such as temperature and pressure were found to have prominent influences on the viscosity of the LDPE melt. Besides that, the flow pattern was observed that polymer melt become straightens towards the extrusion die. The study in simulation of flow of polymer had to consider various parameters. The strength of FLUENT 15.0 in handling simulation of extrusion process needed to study more detail to get excellent and better results.

CHAPTER 1

INTRODUCTION

1.1 Overview

Rheology can be defined as a study of deformation and flow of matter. Extrusions have two types and it parts are introduced in this chapter. There are five basic shapes of products made with extrusion dies which are sheets die, flat film and blown film dies, pipe and tubing dies, profile extrusion dies and co-extrusion dies. The process of polymer flow along the geometrical section of single screw extrusion machine from the feeding zone until die is also presented. This chapter also gives a personal view on the state in relation of the thesis objectives and the scope of study.

1.2 Introduction

Polymeric liquids, namely they are like the liquids that flow and have as constituents, some or all being long chain molecules. This is because polymeric liquids are complex fluids. They exhibit both fluid and solid like behaviour. Some of their dynamic properties may dependent on the history of forces acting on it. An example is "viscosity" which is a function of shear rate, or "viscosity" that changes with time (Sunthar 2010).

The term rheology can be defined as a study of deformation and flow of matter. The special interest is the materials which do not follow the Newton's law of viscosity. Non-Newtonian materials flow in an unusual way where exhibiting various interesting and peculiar flow phenomena. They are further defined as viscoelastic materials. Knowledge on rheological behaviour of polymer needed to find the optimal melt processing conditions. Such as temperature, speed, pressure, rate of flow and for estimating the required machine capacity (Aho 2011).

Rheological properties of polymer melts are particular importance in flow modelling. Simulation software is used to enhance the productivity, quality, turnaround times and resource utilization in polymer processing. It is not only importance for quality of product, but also the cost effectiveness of the whole process. Such as for extrusion process, numerical simulation is achieving an increasingly important role in the part and die design process, as well as in adjusting the right processing parameters for the actual production (Aho 2011).

1.3 Type of Extrusions

According to Paper & Catarina (2013), extrusion is a process used to create objects of a fixed cross-sectional profile. A material is pushed through a die of the desired cross-section. Extrusion may be continuous or semi-continuous (producing many pieces). There are main advantages of this process over other manufacturing processes. It is ability to create very complex cross-sections. It also forms parts with an excellent surface finish.

1.3.1 Type of Extruder

Figure 1.1 shows the schematic of a plasticising single screw extruder. Major extruders are generally classified with a single-screw and a twin-screw type. A single-screw extrusion is applied to general polymer processing such as blow molding, film making and injection molding. It function is to produce a homogeneous melt from the supplied plastics pellets and to press the melt through the shaping die. The screw is the central element of extruder and serves many functions such as transporting the solid feedstock, compressing, melting, homogenizing, and metering the polymer to finally generate sufficient pressure to pump the melt through the die (Sirisinha 1997).

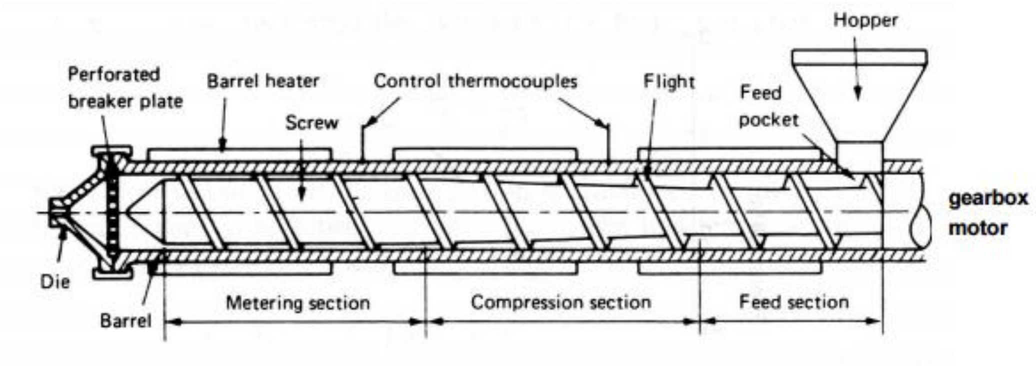


Figure 1.1: Schematic of a single screw extruder (Buckley & Bucknall 1998).

On the other hand, Figure 1.2 shows a twin-screw extruder is mainly used for compounding of various fibers, nano-size fillers and polymer blending prior to final molding. Twin-screw extruders have been developed in particular for continuous mixing purposes compared to single screw extruders, latter are primarily used for high volume metering or pumping. In general, twin-screw extruders can be classified into counter-rotating and co-rotating twin-screw extruders, which are based on non-intermeshing, intermeshing, or close-intermeshing screws.

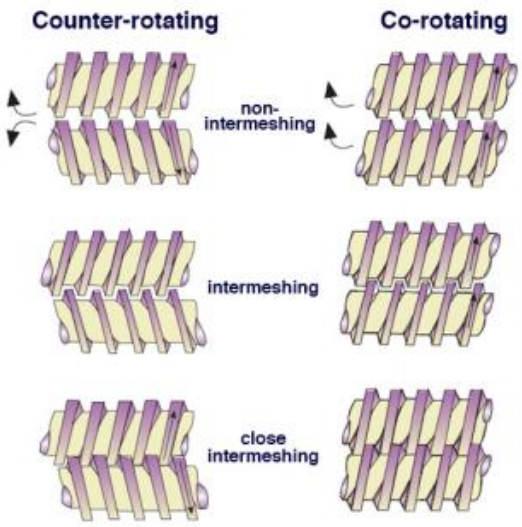


Figure 1.2: Design of different twin-screw extruders (Buckley & Bucknall 1998).

1.3.2 Type of Dies

Flow control devices should be incorporated into the die design to permit fine tuning of the die passage shape to ensure a proper flow balance. In addition, the design of extrusion dies is complicated by two unique material properties of molten plastics. Polymer melts exhibit shear thinning behavior (become less viscous) as they are sheared. Also polymer melts exhibit viscoelastic behavior, which influences the ‘‘die swell’’ on exiting the die. Extrusion dies vary in shape and complexity to meet the demands of the product being manufactured.

There are five basic shapes of products made with extrusion dies. Film and sheet dies are categorized as slit dies since the basic shape of the die exit is a slit. Film is also made with annular dies as in the case of blown film. Strand dies make simple geometric shapes, such as circles, squares, or triangles. Pipe and tubing dies are called annular dies as the melt exits the die in the shape of an annulus. The inner wall of the annulus is supported with slight air pressure during extrusion.

Open profile dies make irregular geometric shapes, such as ‘‘L’’ profiles or ‘‘U’’ profiles, and combinations of these. Hollow profile dies make irregular profiles that have at least one area that is completely surrounded by material. Examples of hollow profiles can be simple, such as concentric squares to make a box beam, or a very complex window profile (Buckley & Bucknall 1998).

1.3.2.1 Sheet Dies

Figure 1.3 shows the coated-hanger type sheet dies. The most common extrusion die for sheet products is the coat hanger-type manifold die. This type of die is typically made for a specific type of polymer such as PET, Free Form PVC, PP Twin Wall, and PVC Siding. It is account for the shear thinning behavior of that polymer.

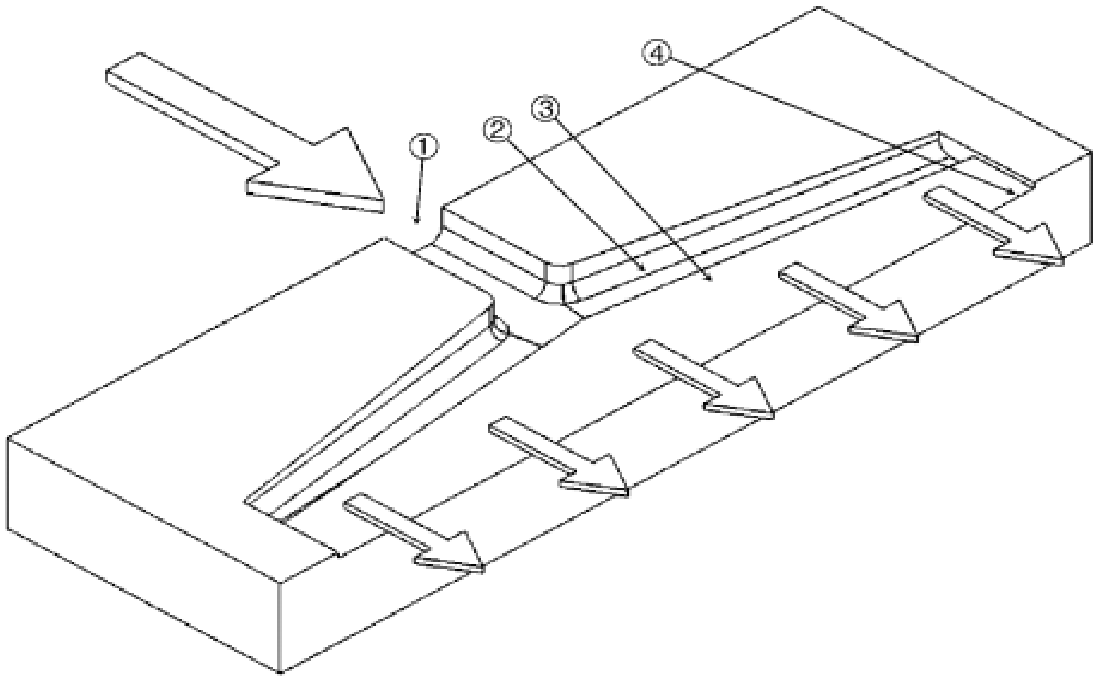


Figure 1.3: Coat hanger-type sheet die concept (A): (1) central inlet port; (2) manifold (distributes melt); (3) island (along with manifold, provides uniform pressure drop from inlet to die lip; (4) die lip (die exit forms a wide slit); and schematic of sheet die (Kostic & Reifschneider 2006).

1.3.2.2 Flat Film and Blown Film Dies

Dies used to make film less than 0.01 in. thick include flat, slit-shaped dies called T-dies and annular dies for blown film were shown at Figure 1.4 and Figure 1.5 respectively. The design of the T-die is similar to the coat hanger-type die with the exception that the manifold. The land length is constant along with the width of the die. A common application for a film die is to coat a substrate like paper.

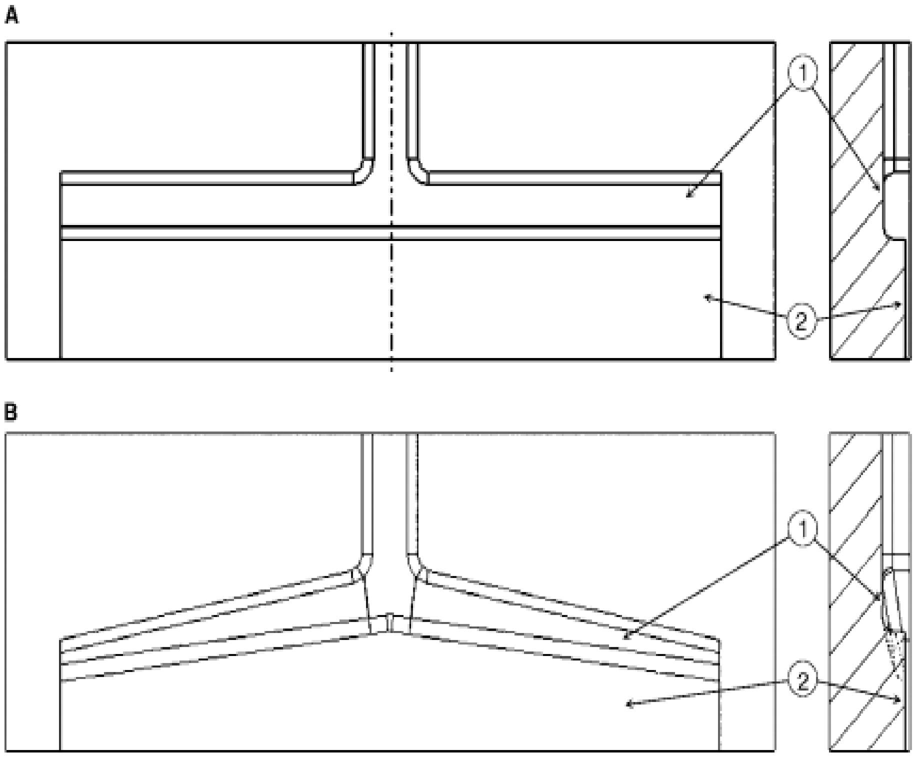


Figure 1.4: Comparing designs of T-type die (A) [(1) constant cross-section manifold; (2) constant land length] to coat hanger-type die (B) [(1) manifold cross-section decreases as distance from centerline increases; (2) land length becomes shorter farther from the centerline of the die (Kostic & Reifschneider 2006).

Blown film dies are the most common way of making commercial films. Because the blown film is so thin, weld lines are not tolerated, and the melt is typically introduced at the bottom of a spiral mandrel through a ring-shaped distribution system, as shown in Figure 1.5.

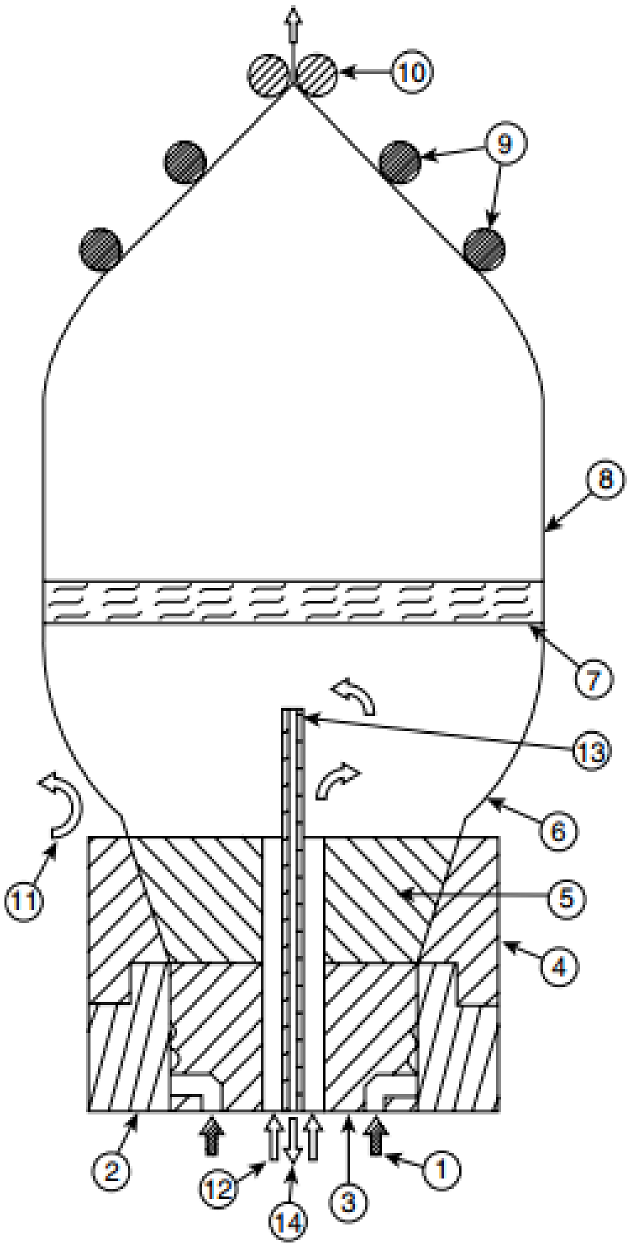
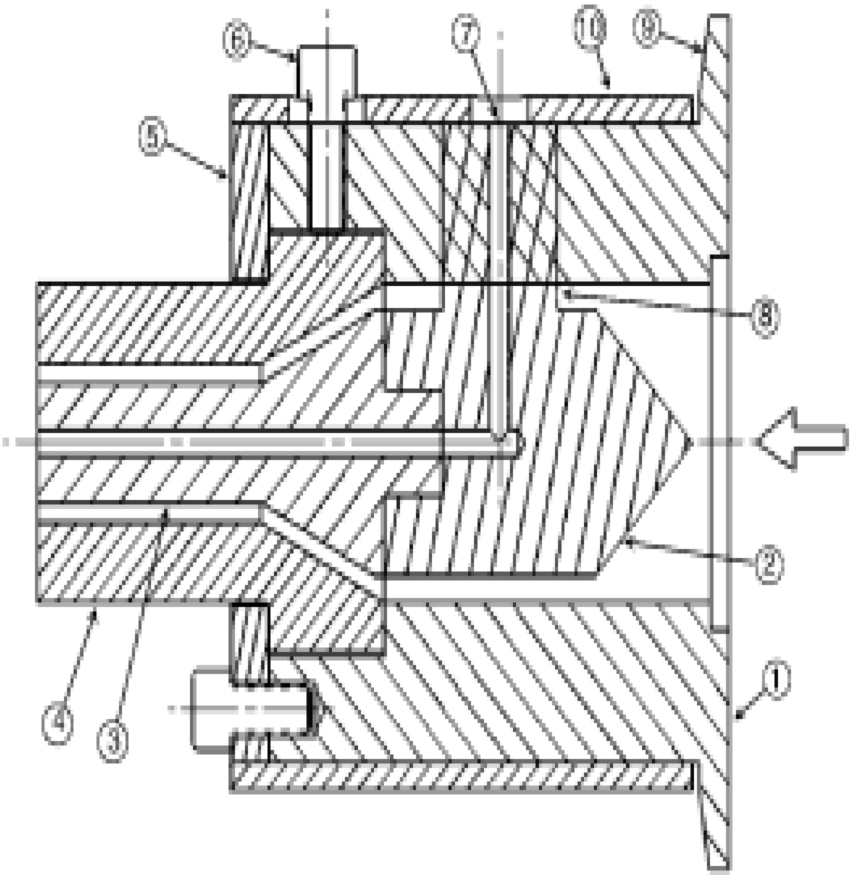


Figure 1.5: Schematic of spiral mandrel blown film die operation: (1) ring-shaped melt distribution; (2) die body; (3) spiral flow mandrel; (4) sizing ring; (5) spreader; (6) film bubble; (7) frost line; (8) solidified film; (9) bubble collapsing rollers; (10) nip rollers; (11) external bubble cooling air; (12) internal bubble cooling air inlet; (13) internal bubble cooling pipe; and (14) heated internal bubble air return (Kostic & Reifschneider 2006).

1.3.2.3 Pipe and Tubing Dies

Both pipe and tubing are made in dies with an annular die exit. A pipe product is defined as being greater than 1 in. in outer diameter and a tube less than 1 in. Dies for these products are made in two styles, in-line dies (also called spider dies) shown in Figure 1.6(A) and cross-head dies shown in Figure 1.6 (B).

A



B

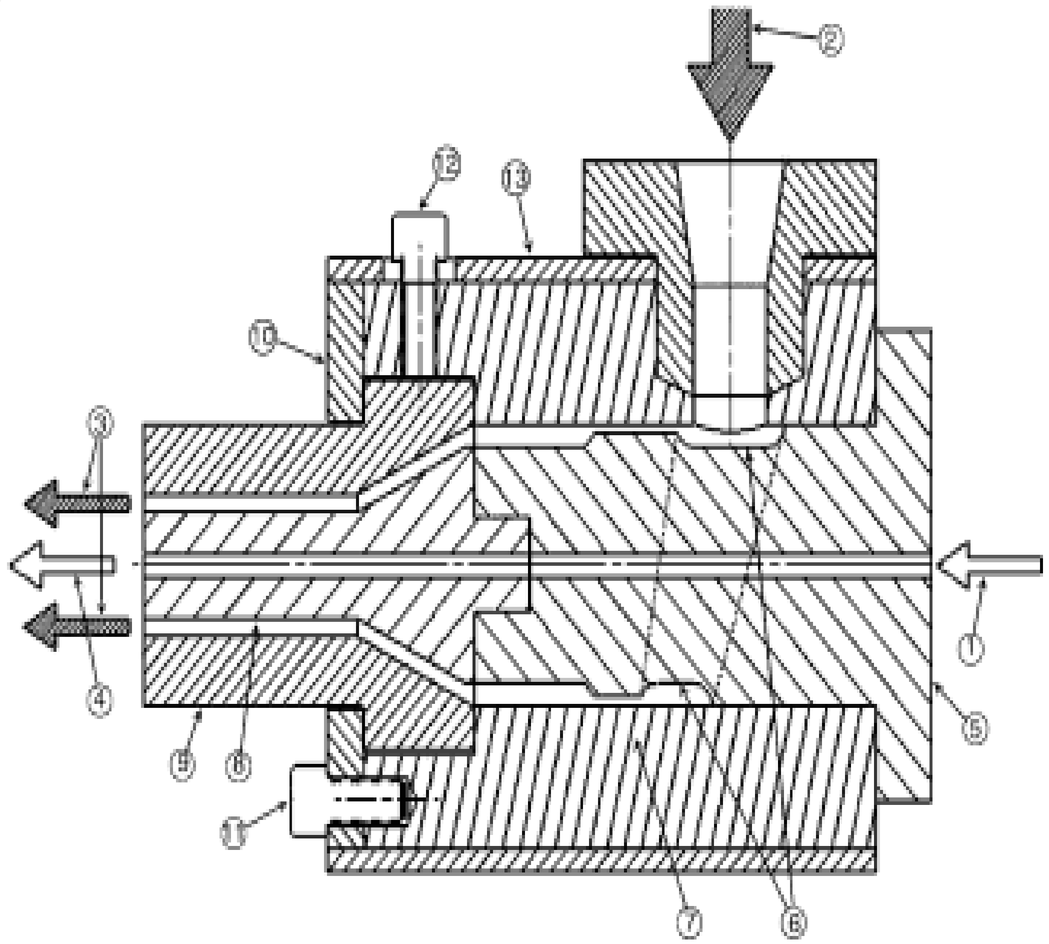


Figure 1.6: Schematic of in-line tubing die (A): (1) housing; (2) mandrel (torpedo); (3) die pin (interchangeable); (4) die land (interchangeable); (5) retaining plate; (6) die centering bolt; (7) air hole; (8) mandrel support (spider leg); (9) die flange (mount to extruder with split clamp); (10) heater band; and cross-head tubing (or wire coating) die (B): (1) air or wire conductor inlet; (2) melt inflow (side inlet); (3) melt exit (annulus); (4) air or wire conductor exit; (5) core tube; (6) flow splitter; (7) housing; (8) die pin; (9) die land; (10) retaining plate; (11) retaining ring bolt; (12) die centering bolt; (13) heater band (Kostic & Reifschneider 2006).

1.3.2.4 Profile Extrusion Dies

Figure 1.7 illustrates a die exit required to achieve a square extrudate. Note that the corners have an acute cups shape and the side walls are not flat. A melt exiting this shape but non-orthogonal shape will swell into a desired, orthogonal square shape.

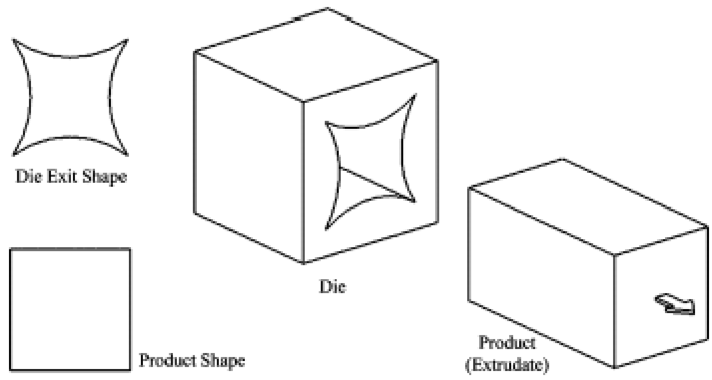


Figure 1.7: Irregular die shapes required for regular extrudates (Kostic & Reifschneider 2006).

Profile extrudates are significantly affected by nonuniform die swell. In the case of profiles with corners and other irregularities, like a square profile, the die exit needed to achieve a square profile is not square owing to the influence of die swell. A critical design rule for open profiles is to maintain a uniform wall thickness throughout the product cross section.

1.3.2.5 Co-Extrusion Dies

Another important product made with extrusion dies is the creation of multi-layered materials. Co-extrusion is the process of extruding two or more materials simultaneously through a single or multi layered die. The materials' flow paths in the die are arranged such that each layer processes individually and merges at the die lip prior to cooling.

1.4 Single Screw Extrusion of Thermoplastic Materials

Figure 1.8 shows the commonly are three-zone screws, since they can be used universally for most thermoplastics. The task of the solids conveying zone in the feed section is to move the polymer pellets or powder from the hopper to the screw channel. The most common feed from the hopper is by gravity (flood feed), the screw continuously extracts the resin it can handle from the hopper.

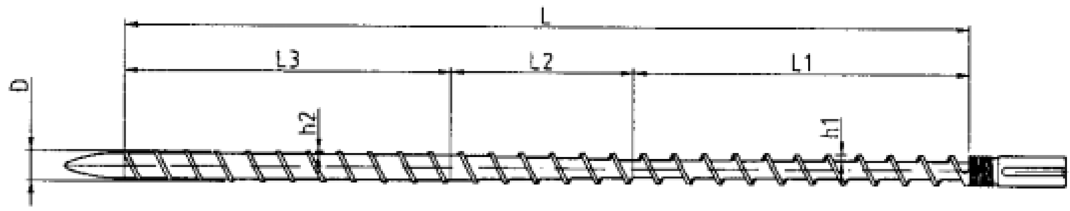


Figure 1.8: Three-zone extrusion screw. D: diameter; L: total length; L1: (length) solid conveying zone/feed section/compaction; L2: Melting/compression/transition zone; L3: metering/pumping zone; h1 and h2: channel depth h (or H) (Buckley & Bucknall 1998).

Once the material is in the screw channel, it is compacted and transported down the channel. Compacting and moving can only be accomplished by friction at the screw surface. The frictional forces result in a pressure rise in the feed section, this pressure compresses the solid bed which continues to travel down the channel as it melts in the compression or melting zone (Buckley & Bucknall 1998).

This effect is amplified by a decreasing channel depth compared to the conveying zone. The metering zone is the most important section in melt extruders and the pressure for sufficient pumping and final melt temperature is generated here. In this section the screw depth is again constant but much less than the feeding zone. In the metering zone the melt is homogenized so as to supply a constant rate, material of