POLYMER PROCESSING

VI Semester BTECH (Chemical Engineering)

• POLYMER PROCESSING – MODULE II

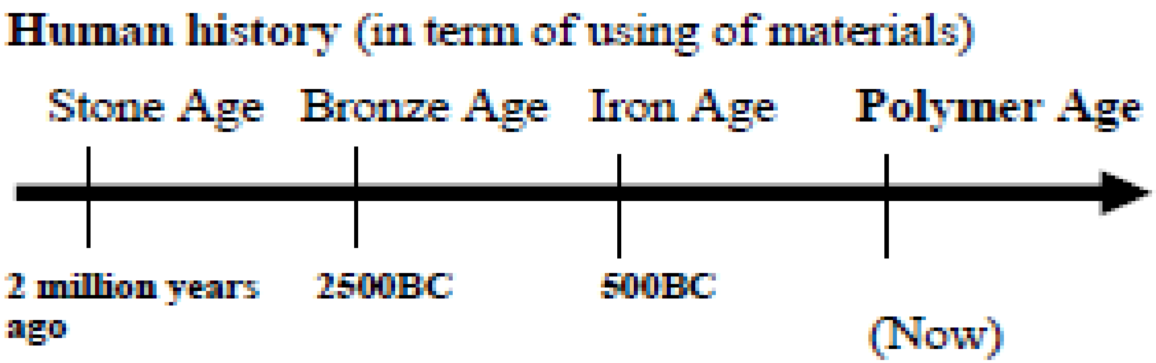
- **Module 2:**
- **Extrusion:** Extruder Classification, Components-Drives, Bearing, Screw, Barrel, Breaker plate, Screen, hopper, Screw geometry, heating & cooling systems.
- **Process analysis**: Solids conveying, plasticating, melt conveying, Melt instabilities.
- **Technology of product manufacturing**: Pipe, Films, Wire coating, Tapes, Monofilaments.

• EXTRUSION – INTRODUCTION

- Extruders are the heart of polymer processing industry.
- Extrude means to push or to force out. (eg., toothpaste is squeezed out of a tube, it is extruded).
- The part of the machine containing the opening through which the material is forced is referred to as **extruder die**.
- As the material passes through the die, the material acquires the shape of the die and the extruded product is referred to as **extrudate**.
- Materials can be extruded in the molten state or in the solid state.
- Generally, polymers are extruded in the molten state, but in some applications involve solid state extrusion of polymers.
- If the polymer is fed to the extruder in the solid state and the material is melted as it is conveyed by the extruder screw from the feed port to die is called **plasticating extrusion**. In this case, it performs additional function namely melting besides regular extrusion function.
- Extruder is fed with molten polymer and called **melt fed extrusion** and it purely acts as a pump developing the necessary pressure to force the polymer melt through the die.

• EXTRUSION – HISTORY

- First machine for extrusion of thermoplastic materials was built around 1935 by Paul Troester in Germany.
- After 1935, extruders evolved to electrically heated screw extruders.
- Around this time, the basic principle of intermeshing co-rotating twin screw extruder was developed by Roberto Colombo.
- Then, Pasquetti developed a different concept of intermeshing counter-rotating twin screw extruder.



- Generally in extrusion, material is softened or melted and forced out under pressure through an orifice that shapes the extrudate to a desired profile or cross-section.

• TYPES OF EXTRUDER

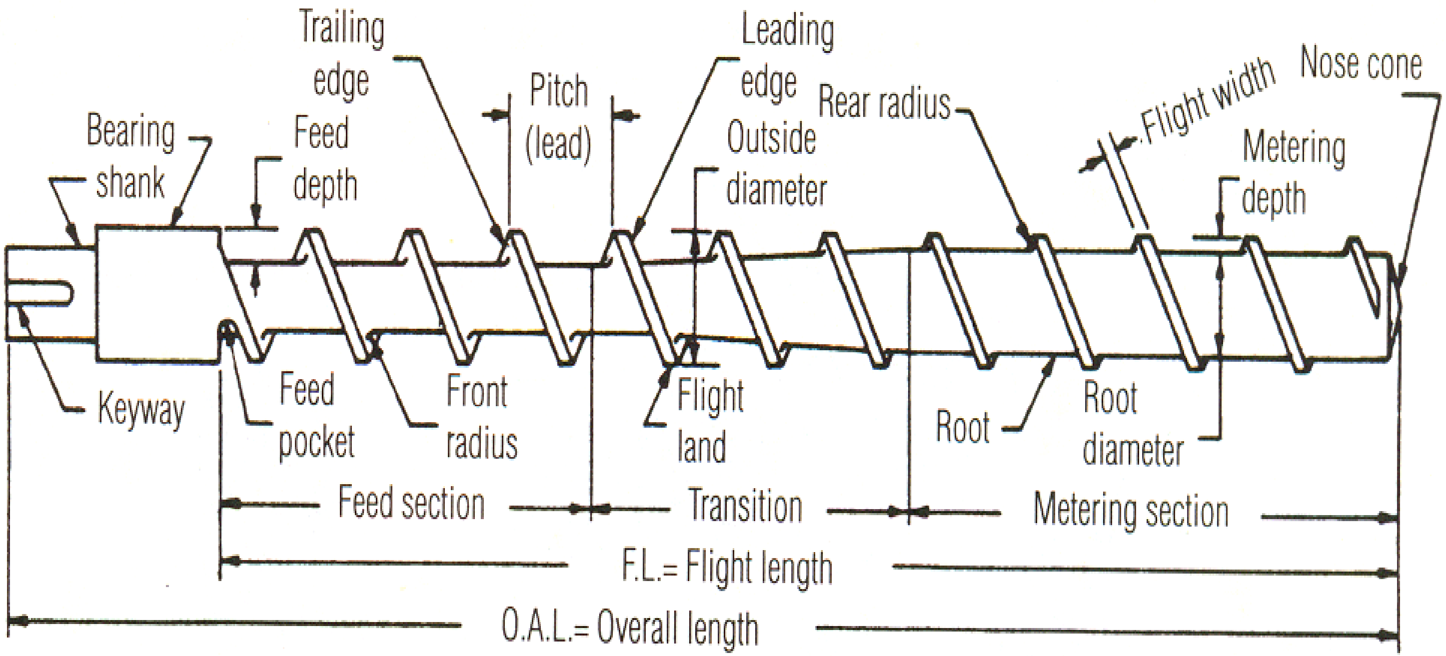
- In polymer industry, extruders come in many different designs.
- Main difference between various extruders is their mode of operation; continuous or discontinuous.
- Continuous extruder are capable of developing steady, continuous flow of material. It utilizes a rotating member for transport of material.
- The batch type or discontinuous extruder operates in a cyclic fashion and it generally have a reciprocating member for the transport of material.
- **CLASSIFICATION OF POLYMER EXTRUDERS**
- Screw Extruder (Continuous)
- Single screw extruder – Melt fed or plasticating, single stage or Multi stage.
- Multi screw extruder – Twin screw extruder, Gear pump.
- Disk or Drum Extruder (Continuous)
- Viscous drag type extruder – Spiral disk, drum, diskpack and stepped disk extru.
- Elastic melt extruder – Screwless extruder and screw/disk extruder
- Reciprocating Extruder (Discontinuous)
- Ram extruder – melt fed and plasticating extruder
- Reciprocating screw extruder – plasticating unit in molding m/cs and compounding extruder

• SINGLE SCREW EXTRUDER

- It is the most important type of extruder used in the polymer industry.
- Advantages are relatively low cost, straightforward design, reliability and favorable performance/cost ratio.
- Conventional extruder have three geometrically different sections such as feed, compression and metering section.
- First section generally has deep flights and it is closest to the feed opening where the material will be mostly in solid state is termed as Feed section.
- Last section usually has shallow flights and it is closest to the die where the material will be mostly in molten state is termed as Metering section.
- The section between feed and metering is called transition or compression section where the depth of the screw channel reduces in a linear fashion from the feed towards the metering section, thus causing a compression of the material in the screw channel.
- Compression section is essential to the proper functioning of the extruder.
- Extruder is usually designated by the diameter of the extruder barrel ie., 20, 25 30, 35, ….600 mm.

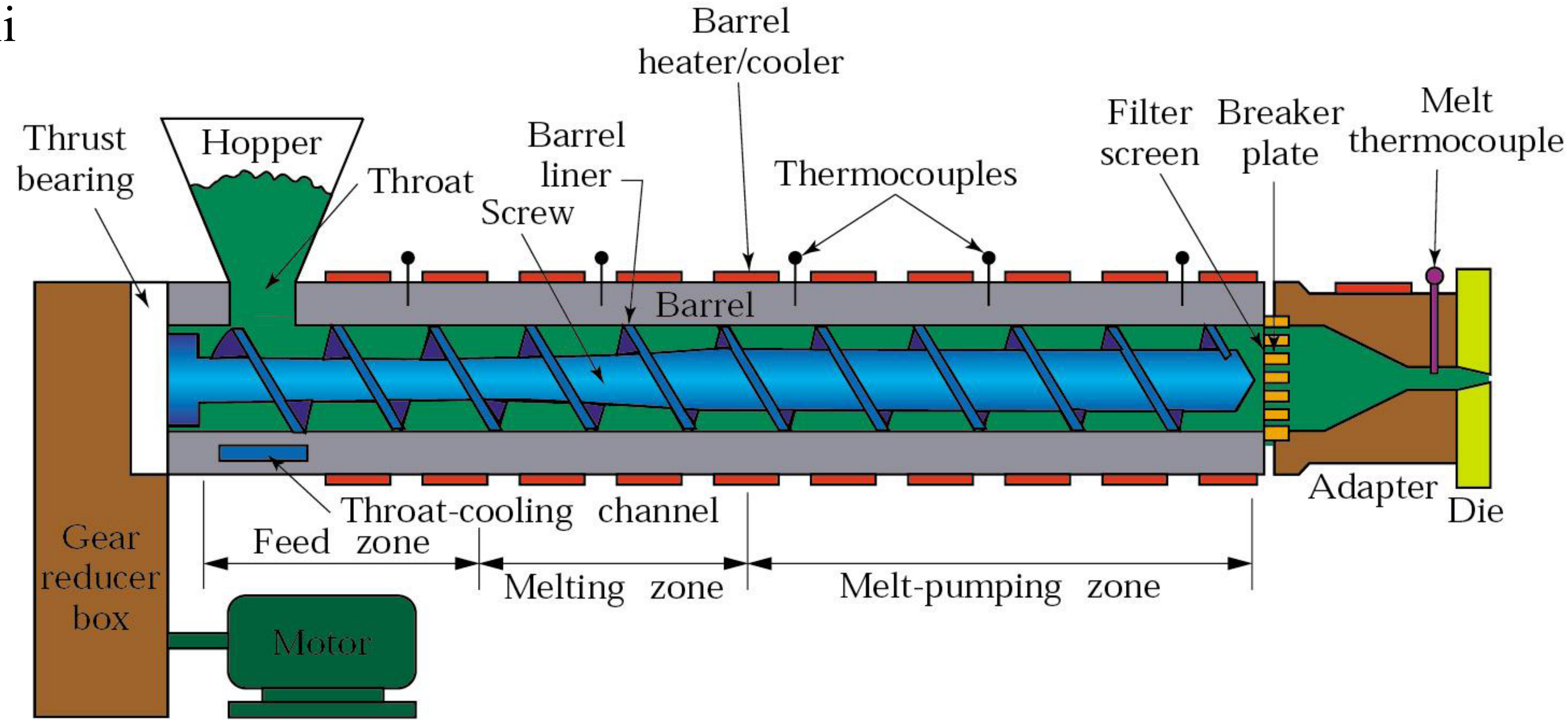
• SINGLE SCREW EXTRUDER

- Another designations are length to diameter ratio (L/D) which is typically range from 20 to 30 with 24 being very common.
- L/D ratio = length of flighted screw / Outside diameter of screw
- Compression ratio = Depth of feed / Depth of metering



• STANDARD EXTRUDER SCREW

- Total length = 20D – 30D Length of feed section = 4D – 8D
- Length of metering section = 6D – 10D No. of parallel flights = 1
- Flight pitch = 1D (helix angle = 17.66º Flight width = 0.1D
- Channel depth in feed section = 0.10D – 0.15D
- Majority of the extruder screw in use today have the general characteristics li

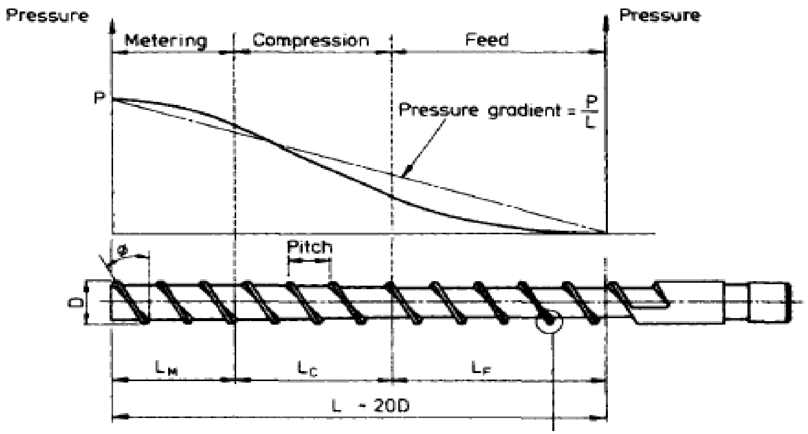


• BASIC OPERATION

- Material enters from the feed hopper by gravity down into the extruder barrel. Some materials will not flow easily in dry form and special care have to be taken to prevent bridging of the material in the feed hopper.
- In the barrel, it is situated in the annular space between the extruder screw and barrel where the barrel is stationery and the screw is rotating. As a result, frictional forces will act on the material. These frictional forces are responsible for the forward transport of the material, atleast as long as the material is in the solid state.
- As the material moves forward, it will heat up as a result of frictional heat generation and heat conduction from barrel heaters.
- The depth of the screw channel is reduced along the length of the screw so as to compact the material.
- Temp. of the mtl. exceeds the melting point, a melt film will be form at the barrel surface where the plasticating zone starts.
- As the material moves forward, the amount of solid mtl. at each location will reduce as a result of melting. When all solid polymers disappeared, the end of plasticating zone has been reached.
- Next, in melt conveying zone, the polymer melt is simply pumped to the die to produce an extrudate of the desired cross-sectional shape.

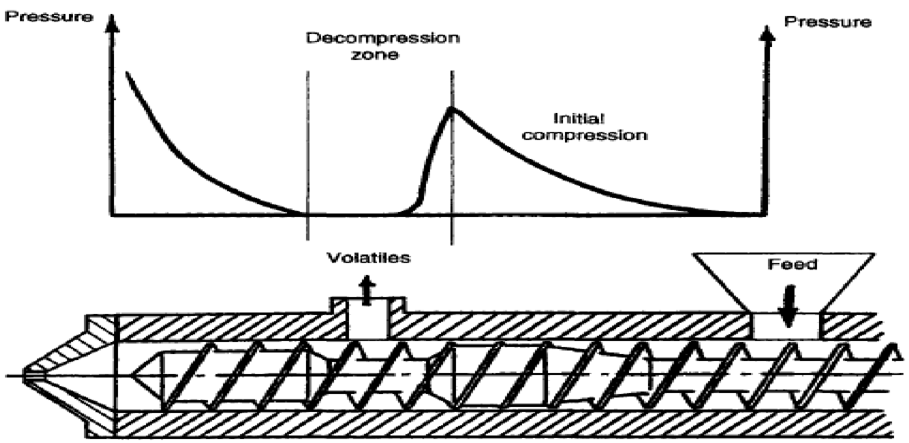
• BASIC OPERATION

- Since the die exerts a resistance to flow, a pressure is required to force the material through the die. It is termed as die head pressure.
- The die head pressure is determined by the shape of the die, the temp. of the polymer melt, flow rate through the die and the rheological properties of the polymer melt.
- The pressure build-up which occurs along a screw



- The lengths of the zones on a particular screw depend on the material to be extruded.
- With nylon, for example, melting takes place quickly so the compression of the melt can be performed in one pitch of the screw.
- PVC on the other hand is very heat sensitive and so a compression zone which covers the whole length of the screw is preferred.

• VENTED EXTRUDER

- Some extruders also have a venting zone.
- Some plastics are hygroscopic in nature - they absorb moisture from the atmosphere, hence vented extruders are necessary.
- If these materials are extruded wet in conventional equipment the quality of the output is not good due to trapped water vapour in the melt.
- Vented barrels were developed to overcome these problems.
- In the first part of the screw, the granules are taken in and melted, compressed and homogenised in the usual way.
- The melt pressure is then reduced to atmospheric pressure in the decompression zone.
- This allows the volatiles to escape from the melt through a special port in the barrel.
- The melt is then conveyed along the barrel to a second compression zone which prevents air pockets from being trapped.
- 

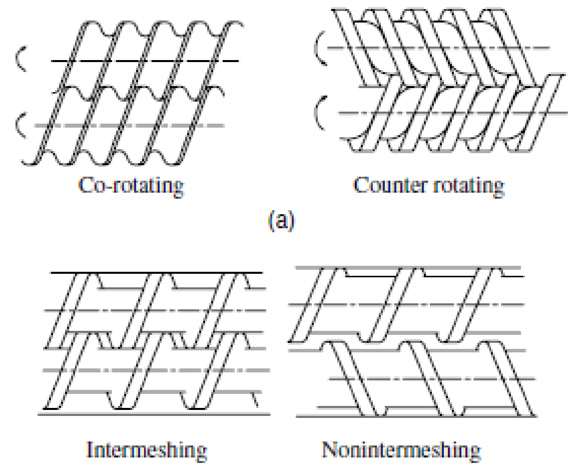
Zones on a vented extruder

• TWIN SCREW EXTRUDER

- It is a extruder with two screws rotating in a heated barrel.
- Variety of twin screw extruders with vast differences in design, principle of operation and field of application.
- Twin screw construction increases the number of design variables such as direction of rotation, degree of intermeshing etc.,
- A general classification of twin screw extruders are:
- Intermeshing Extruder : Co-rotating and Counter-rotating.
- Non-Intermeshing Extruder : Co-rotating and Counter-rotating.
- The screws can co-rotate, in which case the screws have helix angles in the same direction (either right-handed or left-handed), or counter-rotate, in which case, the screws have opposite helix angles.
- The screws can be non-intermeshing or intermeshing, that is, the flight of one screw penetrates into the channel of the other.
- In co-rotating fully intermeshing twin screw, the channel may be continuous, with a smooth transition of material from the channel of one screw to that of the other screw. It is used where mild to intensive compounding must be done. It is well suited for heat sensitive materials.
- In counter-rotating twin screw extruder, the material is effectively squeezed between counter-rotating rolls.

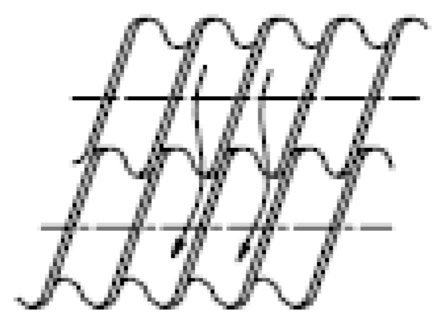
• TWIN SCREW EXTRUDER

- Twin screw extruders permit a wider range of possibilities in terms of output rates, mixing efficiency, heat generation, etc compared with a single screw extruder.
- Disadvantage is complex flow pattern & difficult to describ

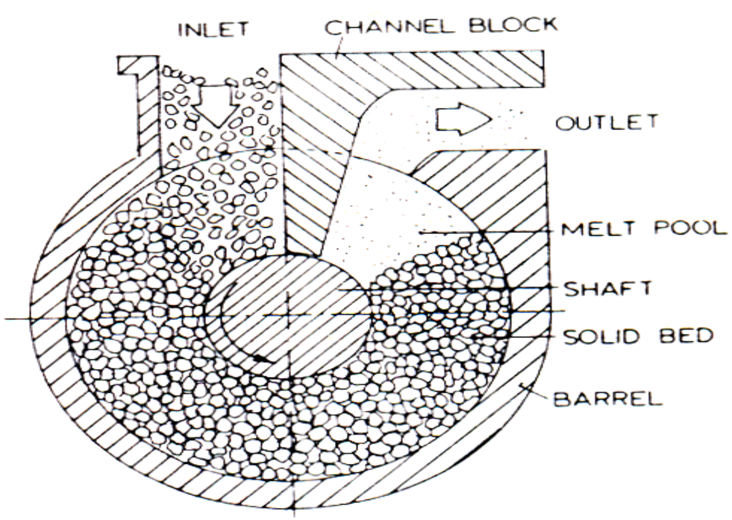


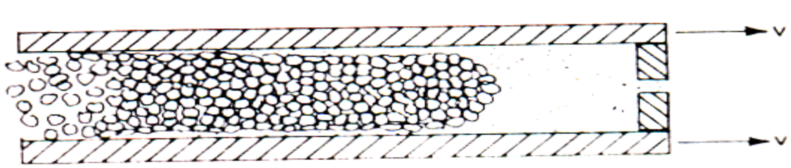
Comparison of single-screw, co-rotating and counter-rotating twin-screw extruders

Type	Single screw	Co-rotating screw: Low speed type	Co-rotating screw: High speed type	Counter-rotating twin screw
Principle	Friction between cylinder and materials and the same between material and screw	Mainly depend on the frictional action as in the case of single screw extruder		Forced mechanical conveyance based on gear pump principle
Conveying efficiency	Low	Medium		High
Mixing efficiency	Low	Medium/High		High
Shearing action	High	Medium	High	Low
Self-cleaning effect	Slight	Medium/High	High	Low
Energy efficiency	Low	Medium/High		High
Heat generation	High	Medium	High	Low
Temp distribution	Wide	Medium	Narrow	Narrow
Max. revolving speed (rpm)	100–300	25–35	250–300	35–45
Max. effective length of screw L/D	30–32	7–18	30–40	10–21



• DISKPACK EXTRUDER

- These type of extruders do not utilize an screw for transport of the material.
- These are referred to as screwless extruders.
- These m/cs employ some kind of disk or drum to extrude the material.
- Material drops in the axial gap b/w relatively thin disks mounted on a rotating shaft.
- The mtl. will move with the disk almost a full turn, then it meets the channel block.
- The channel block deflects the polymer flow to either an outlet channel or to transfer channel in the barrel.
- 



- DRUM EXTRUDER
- Mtl. Is fed by a feed hopper into an annular space b/w rotor & barrel.
- By the rotation of the rotor, the mtl. Is carried along the circumference of the barrel.
- Before the mtl. Reaches the hopper, it encounters a wiper bar, this deflects the polymer flow into a channel that leads to the extruder die.
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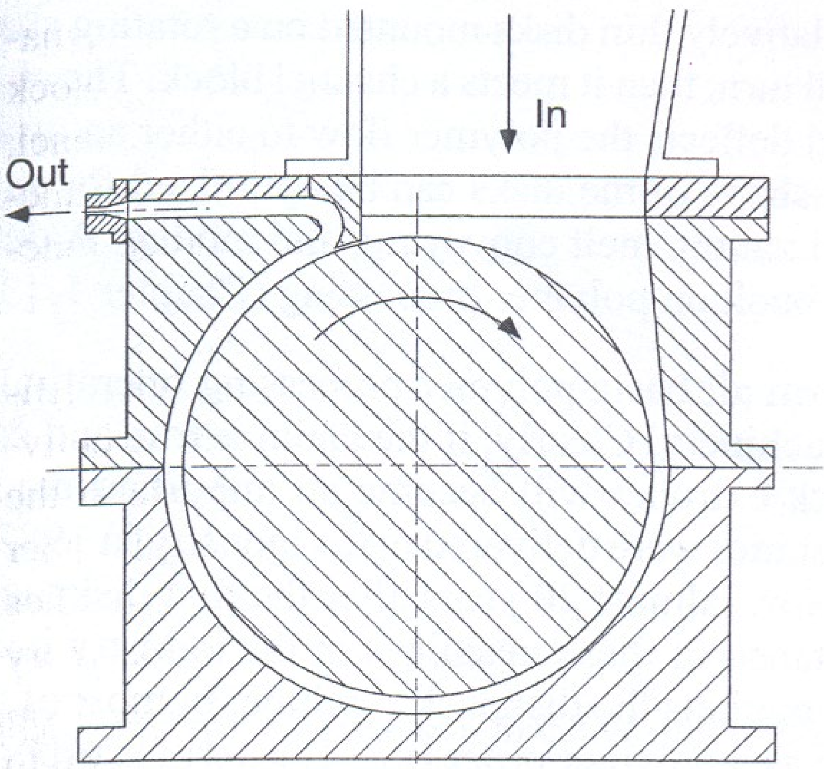
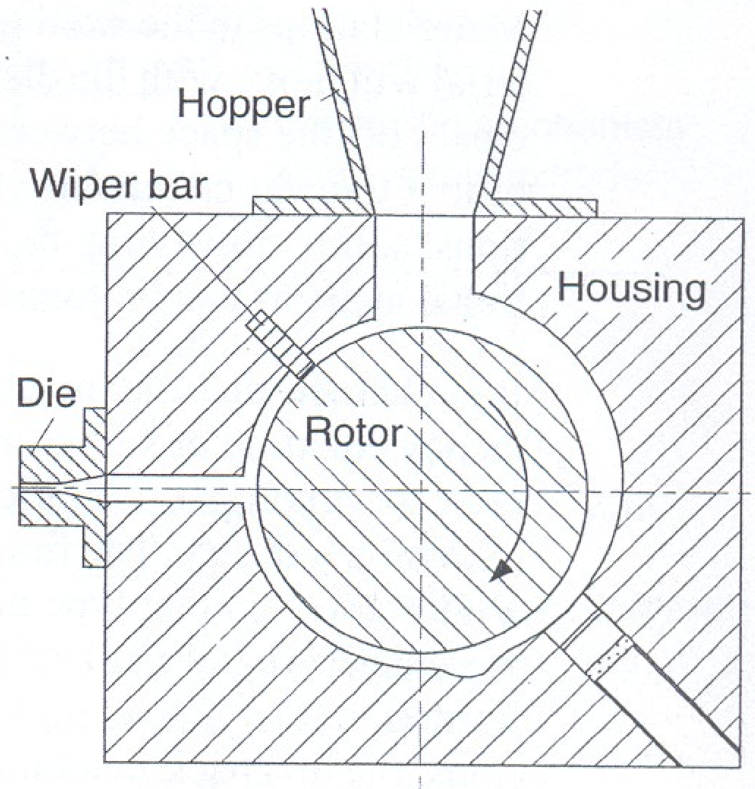


The drum extruder by Schmid & Kocher



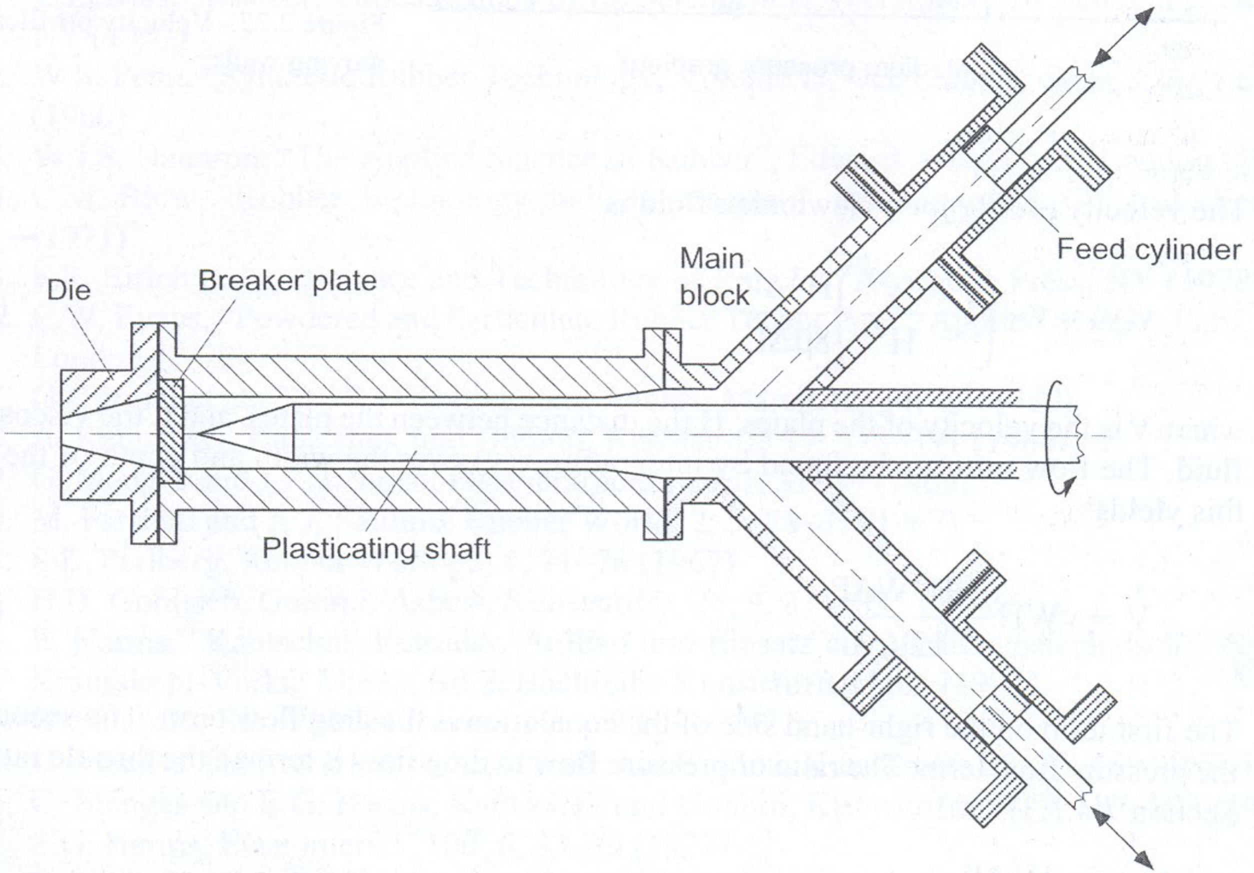
The drum extruder by Asko/Cosden

RAM EXTRUDER

- Ram or plunger extruders are simple in design & discontinuous in their mode of operation.
- They are able to generate very high pressures.
- Limitations for switch to reciprocating screw extruders are: limited melting capacity, poor temp uniformity of polymer melt.
- Used in relatively small shot size molding machines and outstanding pressure generation capability is needed.
- Two types of ram extruders are: Single ram and Multi Ram.
- **SINGLE and MULTI RAM EXTRUDER**
- It is used in small general purpose molding m/c but also in some special polymer processing operations such as Ultrahigh molecular weight polyethylene & polytetrafluoroethylene (PTFE).
- These polymers are not considered to be melt processable on conventional melt processing equipment.
- Ram are used to mold UHMWPE under very high pressure. The m/c uses a reciprocating plunger that densifies the cold incoming mtl with a pressure upto 300 Mpa.
- The mtl is forced to heated channels into the heated cylinder where final melting takes place.
- The mtl is then injected into the mold by injection ram.
- Another application is the extrusion of PTFE material with very high pressure is required.
- The main disadvantage are discontinuous o/p. Hence multi ram extruder are developed.

• RAM EXTRUDER

- In this type, the two rams discharge mtl into a common barrel in which plasticating shaft is rotated.
- The m/c is able to extrude but the throughput uniformity is poor.



Twin ram extruder

• MAIN ELEMENTS OF EXTRUDER-HOPPER

- Feed hopper (a metallic cylinder with a converging section) feeds the granular material to the extruder screw.
- In most cases, the mtl will flow by gravity, but in some cases it will not flow steadily eg. Bulk materials which has very poor flow characteristics.
- In such cases, vibrator pad an additional device is attached to the hopper & stirrers are used to mix the mtl & wipe the mtl when sticks to the wall. (Eg., Crammer Feeder).
- Mtl with low bulk density tends to entrap air, so it will affect the product & sometimes small explosions when the air escapes from the die. Hence Vacuum feed hopper is used.
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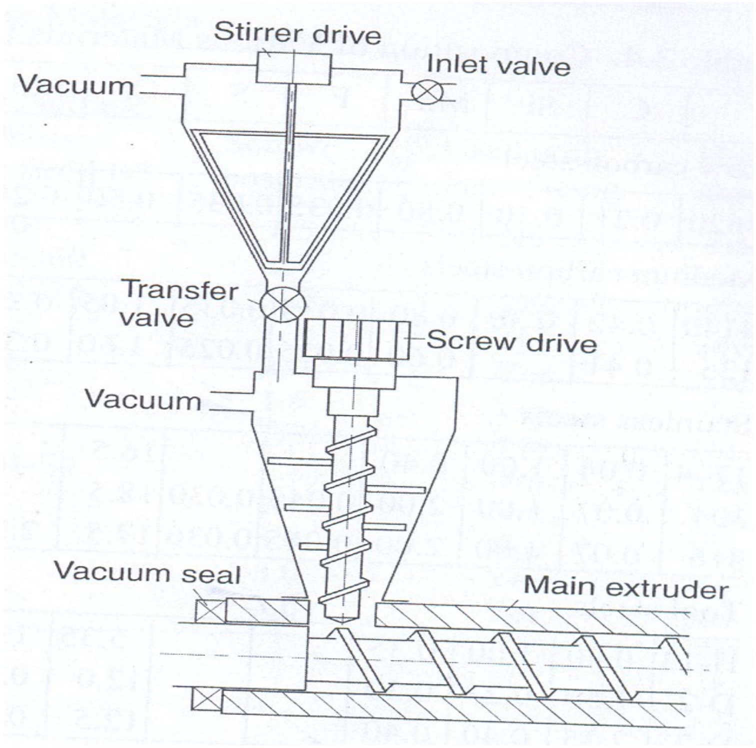

• MAIN ELEMENTS - BARREL AND FEED THROAT

- The extruder barrel is the cylinder that surrounds the screw.
- The feed throat is the section of the extruder barrel where the mtl is introduced into the screw, it fits around the first few flights of the screw.
- Shape of the feed throat is usually circular or square. Geometry of feed throat is such that mtl flow with minmium restriction.
- Smooth transition from feed hopper to feed throat will occur if the cross sectional shape of the hopper is the same as the shape of the feed opening.
- Different feed port designs are: a) is the usual feed port. B) shows an undercut feed port commonly used on melt fed extruders. The wedge section between screw and feed opening causes problem when the melt is relatively stiff or highly elastic, significant lateral forces will act on the screw, hence deflect the screw and force it against the barrel surface. It will be more severe when it is used for feed solid polymer.
- C) It has an undercut to improve the intake capability and the wedge is eliminated by a flat section.
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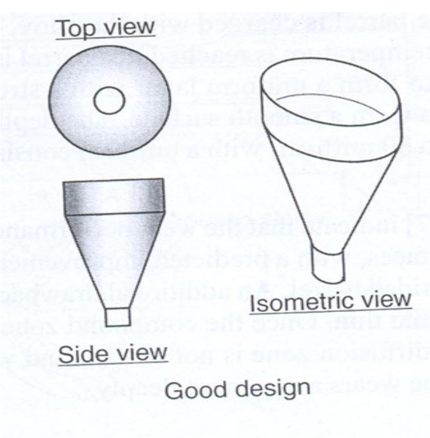

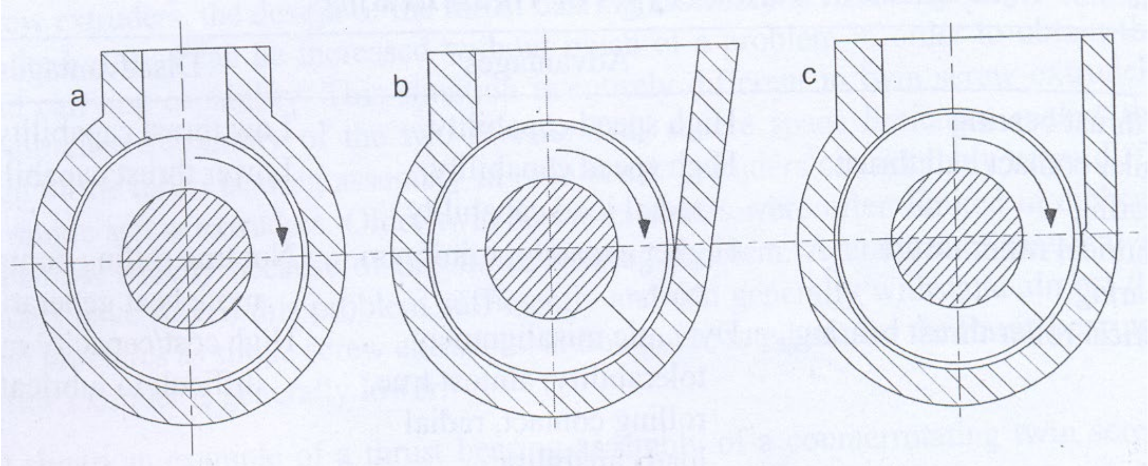

MAIN ELEMENTS-BARREL AND FEED THROAT

- Barrel is a flanged cylinder and has to withstand high pressure of about 70MPa and should posses good structural rigidity to minimize deflection.
- It is preferably made with wear resistant inner surface to increase the service life. Common techniques are nitriding and bimetallic alloying.
- Sometimes, extruders are equipped with grooved barrel section. The depth of the grooves varies with axial distance. The depth is maximum at the start and reduces to zero where it meets with the smooth extruder barrel.
- Important requirement in the feed section design are: Very good cooling capability, Good thermal barrier b/w feed section and barrel and Large pressure capability.
- Large amt of frictional heat generated, hence good cooling is required. To minimize the heat flow from the barrel to the feed section, hence thermal barrier is required. Large pr. Will be generated in the grooved barrel section.
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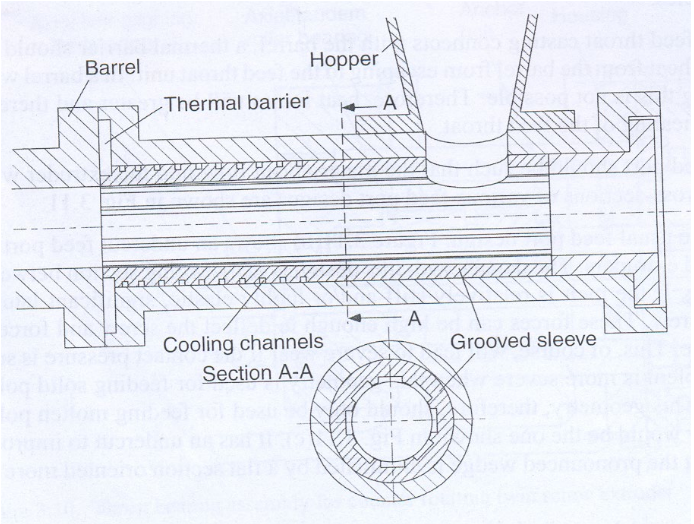

• MAIN ELEMENTS-BREAKER PLATE AND SCREEN

- The output end of the barrel is provided with breaker plate and screen pack b/w barrel and die assembly.
- The breaker plate is a thick metal disk with many closely spaced parallel holes, parallel to the screw axis.
- The reasons for using breaker plate is 1) to arrest the spiraling motion of the melt and to force the polymer melt in a straight line. 2) is to put screen infront of the breaker plate as it acts as a support for the screens.
- Screens are generally used for filtering contaminants out of the polymer. The coarsest screen (lowest mesh number) is usually placed against the breaker plate for support with successively finer screens placed against it. A typical screen pack is one 100 mesh followed by 60 mesh and one 30 mesh screen.
- It also assist the build up of back pressure which improves mixing along the screw.
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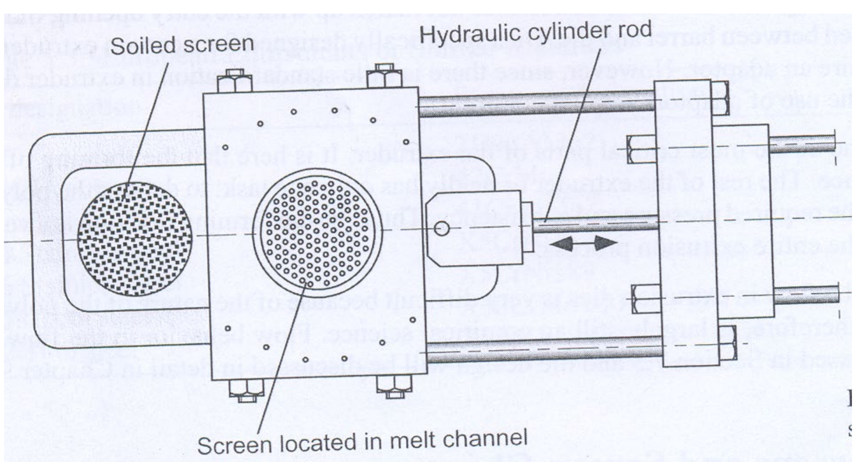

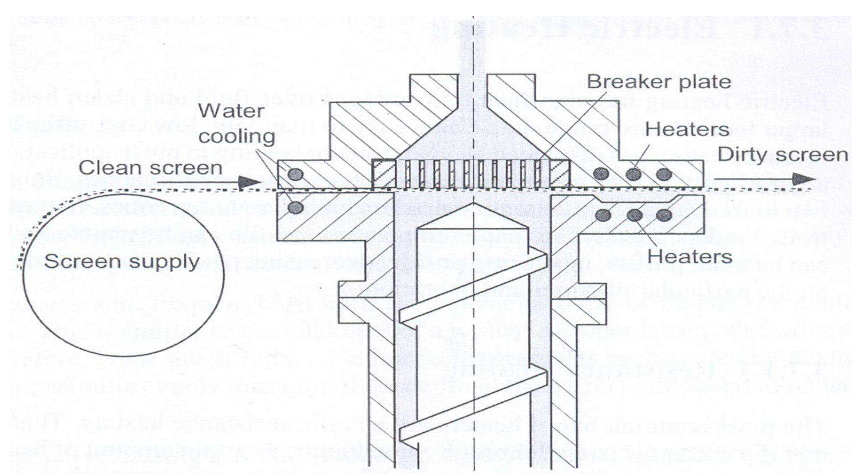

- MAIN ELEMENTS-BREAKER PLATE AND SCREEN

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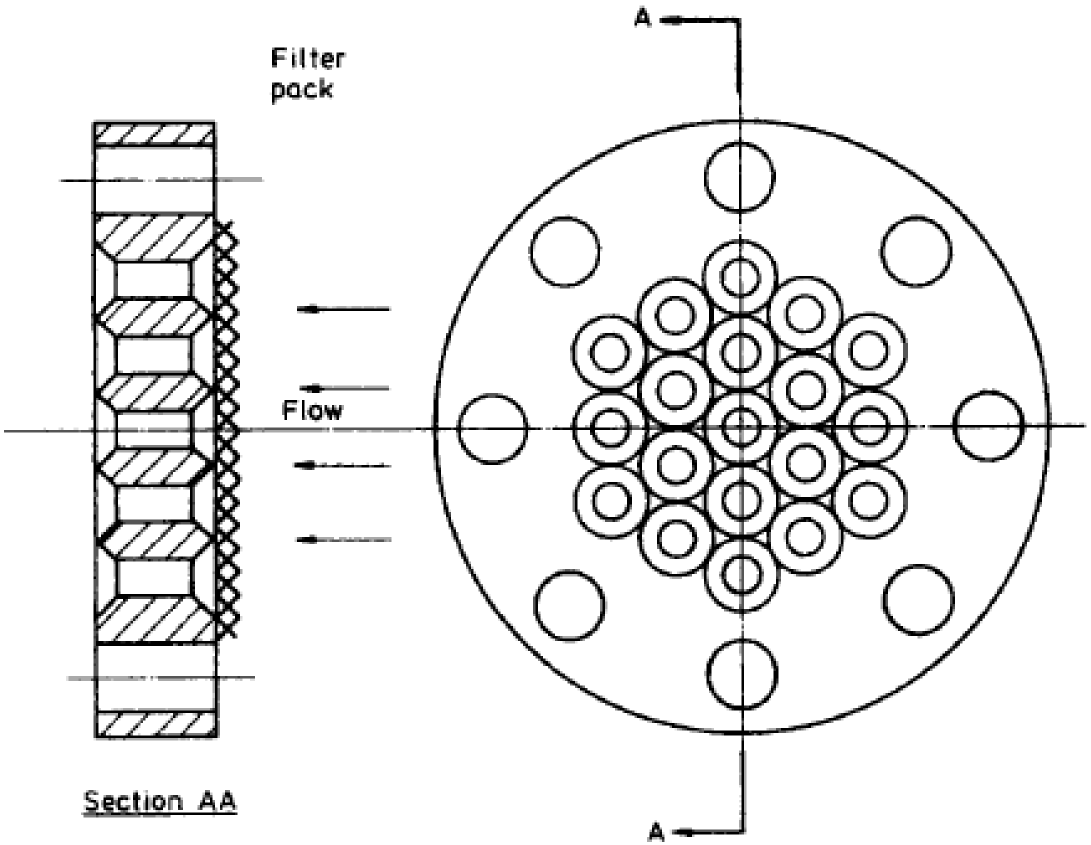


Fig. 4.6 Breaker plate with filter pack

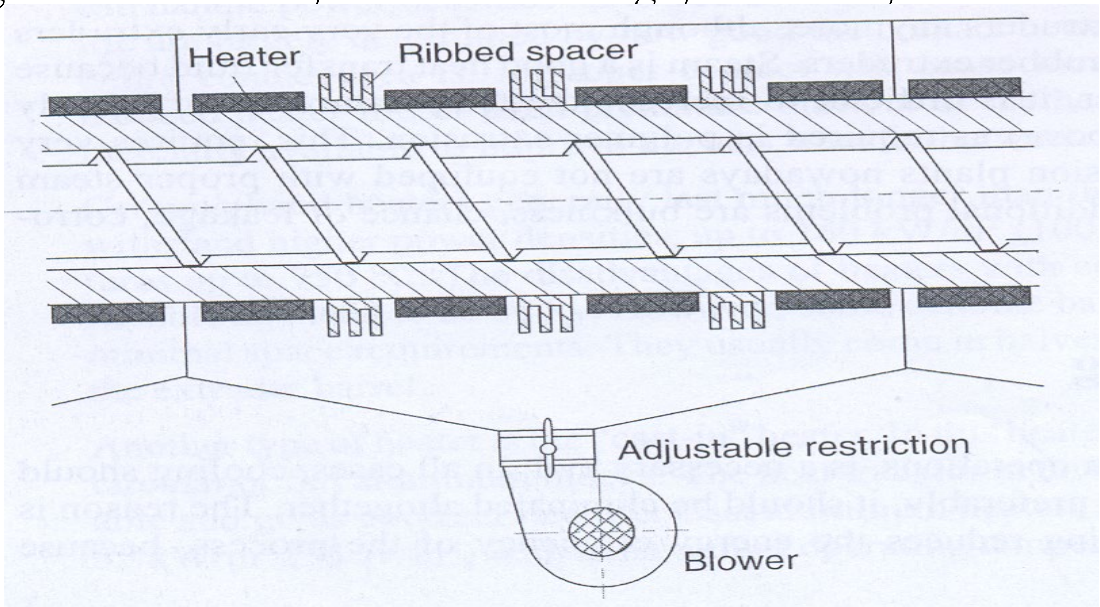
EXTRUDER HEATING & COOLING SYSTEMS

- Extruder heating is required for bringing the m/c setup to the proper temp for start up & for maintaining the desired temp under normal conditions.
- Three types of heating extruders: Electric heating, Fluid heating and Steam heating.
- Electric heating: It has advantage over fluid and steam heating as it can cover a much larger temp range, clean, easy to maintain, low cost, efficient etc.,
- Electrical heaters are normally placed along the extruder barrels grouped in zones. Small extruders will have two to four zones, while large extruders have five to ten zones.
- Each zones is controlled independently, so that a temp profile can be maintained along the extruder.
- Two types of Electrical heaters: Resistance heating and Induction heating
- Resistance heating: Most common barrel heaters. It works on the principle, that if a current is passed through a conductor a certain amount of heat is generated, depending on the resistance of the conductor.
- Early band heaters used a resistance wire insulated with mica strips and encased in flexible sheet steel covers. These are compact and low cost, but they are also fragile, not very reliable and have limited power density. Maxi loading is about 50 kW/m2 and maxi temp about 500 deg C. The efficiency and its life of heaters are determined by the contact b/w the heater and the barrel over the entire contact area. Improper contact will have local overheating will result in reduced heater life.

EXTRUDER HEATING & COOLING SYSTEMS

- Ceramic band heaters generally last much longer than the mica heaters and they can withstand higher power densities upto 160 kW/m2 and temp to 750 deg C. The disadvantage is that they are not flexible and tend to be bulky. They usually come in halves that have to be bolted together around the extruder barrel.
- In Cast-in heater, the heating elements are cast in semi-circular or flat aluminium blocks. The heat transfer of this heater is very good. It is reliable and gives good service life. Cast aluminium heaters have power density of 55 kW/m2 and temp of 400 deg C. Bronze castings has power density of 80 kW/m2 and temp of about 550 deg C.
- INDUCTION heating: An alternating electric current is passed through a primary coil that surrounds the extruder barrel. The AC causes an alternating magnetic field of the same frequency. This magnetic field induces an electromotive force in the barrel, causing eddy-currents.
- The depth of heating reduces with frequency. At normal frequencies of 50 or 60 Hz, the depth is approximately 25mm which is similar to the thickness of a typical extruder barrel.
- The heat is generated quite evenly throughout the depth of the barrel as opposed to resistance type barrel heaters.
- The advantage is reduced time lag in power input changes and Local overheating because of poor contact does not occur. Power consumption is low due to efficient heating and reduced heat losses.
- The disadvantage of this heating system is its high cost.

• EXTRUDER HEATING & COOLING SYSTEMS

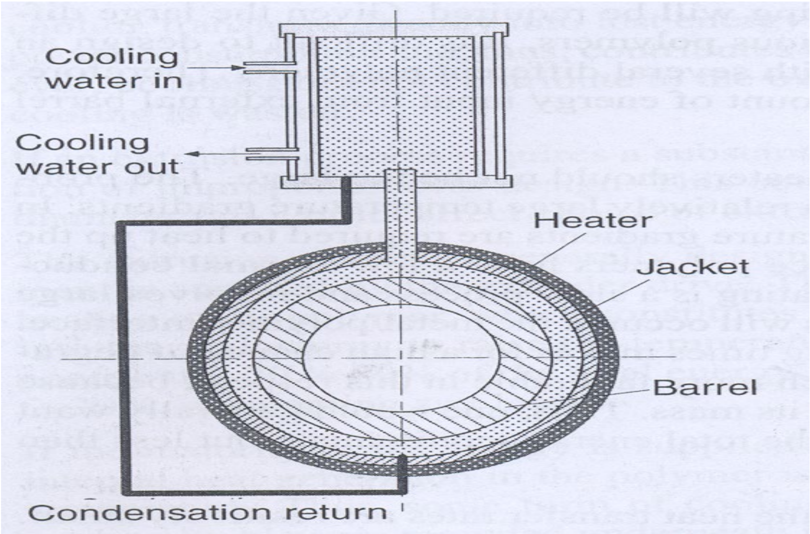
- FLUID heating allows even temp over the entire heat transfer area avoiding local overheating.
- The maxi operating temp of most fluids is relatively low generally below 250 deg C.
- It requires considerable space, installation and operating expenses are high.
- Another drawback is that if several zones need to be maintained at different temp several independent fluid heating systems are required. Hence expensive, bulky and ineffective.
- STEAM heating is rarely used on extruders anymore, although most of the very early extruders were heated by this way. Steam is a good heat transfer fluid because of its high specific heat. However, it is difficult to increase the temp to sufficiently high temp 200 deg C and over as required in extrusion. Very high steam is required.
- Disadvantages are bulkiness, chance of leakage, corrosion, heat losses etc.,
- 

EXTRUDER HEATING & COOLING SYSTEMS

- Extruder cooling is necessary in most extruder operations. In all cases, cooling should be minimized as much as possible or eliminated altogether.
- Extruder cooling reduces the energy efficiency of the process. As well as it does not contribute to the overall power requirement and the energy extracted by cooling is wasted.
- If extrusion process required cooling, it is usually a strong indication of improper process design such as improper screw design, excessive L/D ratio or incorrect choice of extruder.
- Generally extrusion process is designed such that the majority of the total energy requirement is supplied by the extruder drive. The rotation of the screw causes frictional and viscous heating of the polymer, which constitutes a transformation of mechanical energy into thermal energy to raise the temp of the polymer. The mechanical energy generally contributes 70 to 80 % of the total energy and the extruder heaters contribute only 20 to 30 %, discounting any losses.
- Majority of the energy supplied by the screw, hence there is a chance that local internal heat generation in the polymer is higher than required to maintain the desired process temp. Thus some form of cooling is required. Hence forced air cooling by blowers are used.
- Some extruders operate without any forced cooling or heating. It is referred as autogenous extrusion process.
- It is a process where the heat required is supplied entirely by the conversion of mechanical energy into thermal energy.
- But in practical autogenous extrusion does not occur often because it required a delicate balance b/w polymer properties, m/c design and operating conditions.

• EXTRUDER HEATING & COOLING SYSTEMS

- Change in any of these factors will generally cause a departure from autogenous conditions. Hence most of the extruders are designed to have a reasonable amount of energy input from external barrel heaters.
- Air cooling is a fairly gentle type of cooling and change in temp occurs gradually, because heat transfer rates are relatively small. But when intensive cooling is required, it is not good. With water cooling, a rapid and steep change in temp will occur. From control point of view, water cooling is difficult to handle. Grooved barrel sections will require intense cooling hence water cooling is used.
- Finally, it should be always be remember, that Cooling is a waste of energy and should be minimized as much as possible.



- THRUST BEARING ASSEMBLY

- Thrust bearing assembly is usually located at the point where the screw shank connects with the output shaft of the drive, which is generally the output shaft of the gear box.
- It is required because the extruder generally develops substantial die head pressure in the polymer melt. This die head pressure is necessary to push the polymer melt through the die at the desired rate.
- However, since action = reaction, this pressure will also act on the extruder screw and force it towards the feed end of the extruder.
- Therefore thrust bearing capability has to be available to take up the axial forces acting on the screw.
- The actual force on the screw is obtained by multiplying the diehead pressure with the cross sectional area of the screw.
- For eg., a 150mm extruder running with a die head pressure of 35 Mpa will experience an axial thrust of about 620 kN. Hence significant forces are acting on the screw and proper design and dimensioning of the thrust bearing is required to the trouble free operation of the extruder.
- Thrust bearings are designed to last a certain number of revolutions at a certain thrust load.
- Under normal operating conditions and die head pressure, the thrust bearing will generally last as long as the life of the extruder.
- However, if sharp fluctuations in die head pressure occurs, the life of bearing can reduce dramatically.
- Thrust bearing assembly consists of four or five roller bearings.

• THRUST BEARING ASSEMBLY

- Extruder manufacturers often give the rated life of thrust bearing as a B-10 life. Ie 10 out of 100 identical group of bearing will fail before rated life.
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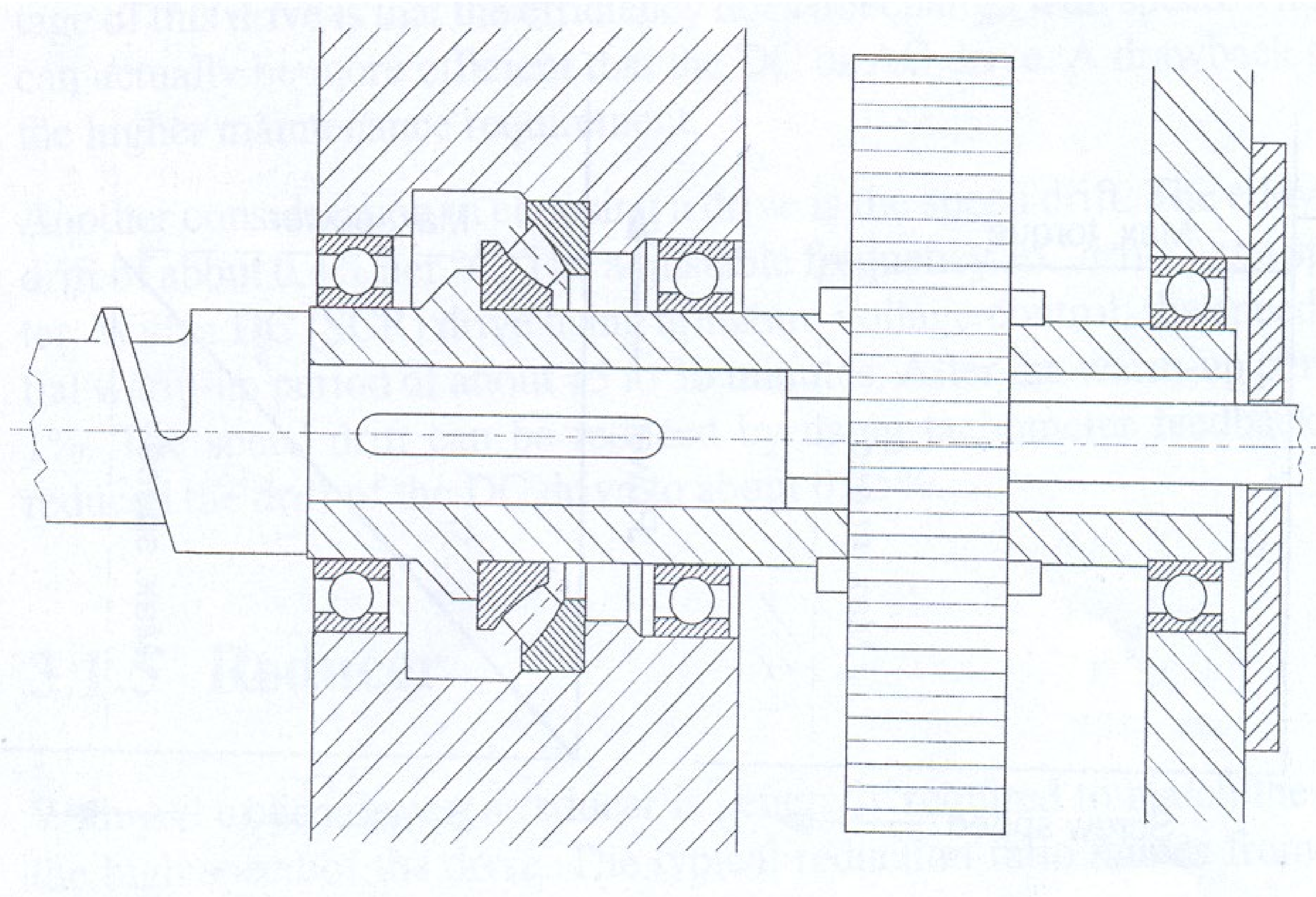
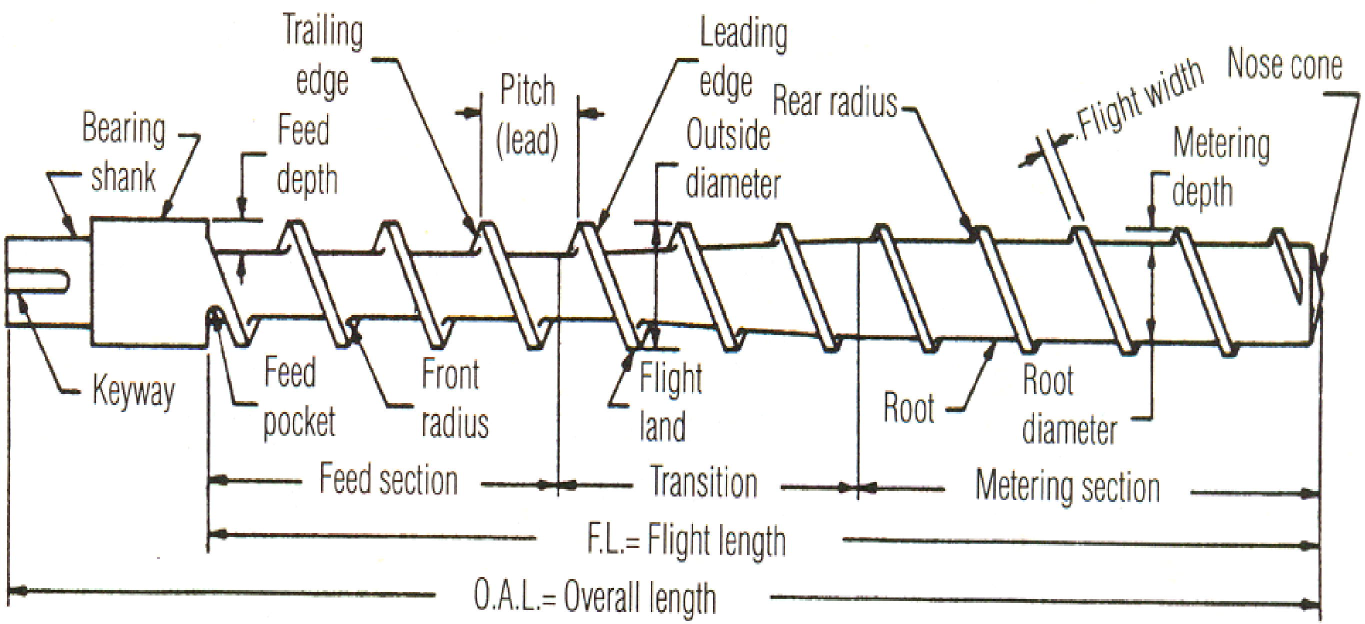


EXTRUDER DRIVES

- Extruder drives are used to turn the extruder screw at the desired speed.
- It should be able to maintain a constant screw speed because fluctuations in screw speed will result in throughput fluctuations which in turn cause fluctuations in the dimensions of the extrudate.
- The drive also able to supply the required amount of torque to the shank of the extruder.
- Another requirement is the ability to vary the speed over a relatively wide range from almost zero to maximum screw speed.
- Main drive systems employed on extruders are: AC motor drive system, DC motor drive system and hydraulic drives.
- AC motor drive system used on extruders are adjustable transmission ratio drive and adjustable frequency drive.
- Adjustable transmission ratio drive can be either mechanical adjustable speed drive using belt or chain drives or electric friction clutch drive.
- Adjustable frequency drive uses an AC squirrel cage induction motor connected to a solid state power supply capable of providing an adjustable frequency to the AC motor.
- DC motor drive uses fixed AC motors to drive DC generators that produce the variable voltage for the DC motor.
- Hydraulic drive generally consists of a constant speed AC motor driving a hydraulic pump which in turn drives hydraulic motor and associated controls.

- # EXTRUDER SCREW

- Extruder screw is the heart of the machine.
- The rotation of the screw causes forward transport, contributes to a large extent to the heating of the polymer, and causes homogenization of the material.
- Simply, Screw is a cylindrical rod of varying diameter with a helical flights wrapped around it.
- The outside diameter of the screw is constant on most extruders.
- Clearance between screw and barrel is usually small, generally the ratio of radial clearance to screw diameter is around 0.001.
- Common screw material is 4140 steel, which is medium carbon and relatively low cost. Some of other
- 

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- EXTRUDER SCREW GEOMETRY

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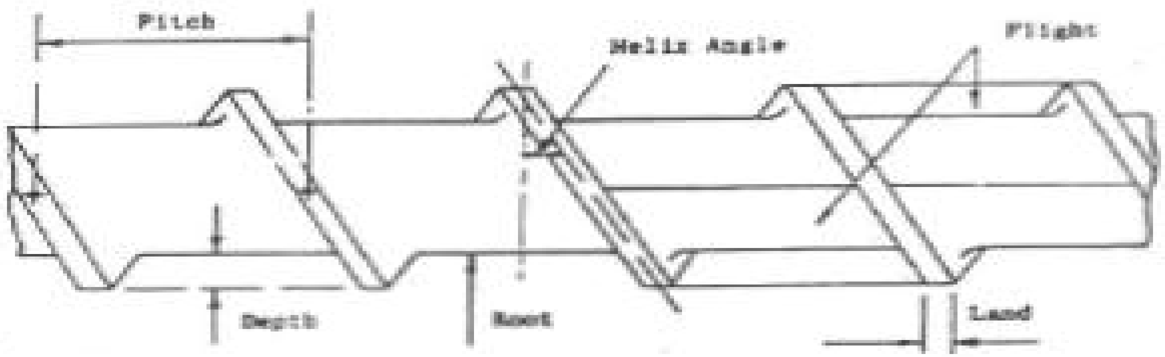
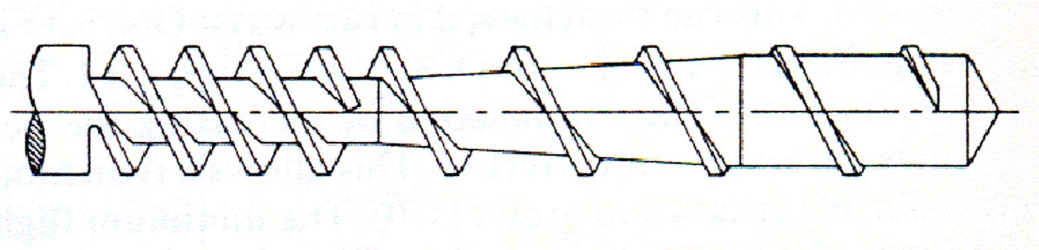
- Screw Definitions



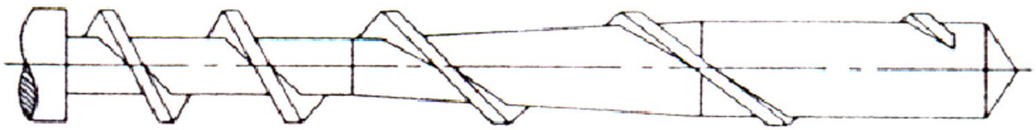
1.	Depth	the perpendicular distance from the top of the thread to the root surface
2.	Flight	-the space enclosed by the thread and the surface of the root in one complete turn of the screw
3.	Helix Angle	the angle between the screw thread and the transverse plane of the screw
4.	Land	the surface at the radial extremity of the screw thread constituting the periphery or outside diameter of the screw.
5.	Lead	the horizontal distance travelled by the material in one complete revolution of the screw, assuming 100% efficiency. It is equal to the pitch multiplied by the number of starts.
6.	Number of starts	the number of separate threads traced along the length of the screw.
7.	Pitch	the horizontal distance between corresponding points of two successive lands.
8.	Root	the continuous central shaft, usuallyof cylindrical or conical shape.

• MODIFICATIONS OF SCREW

- **Standard screw with additional flight in feed section:** Forces acting on the screw are balanced, thus screw deflection is less likely to occur.
- To smooth out the pressure fluctuations caused by the flight interrupting the inflow of material from feed hopper every revolution of the screw.
- Negative side is reduces the cross sectional area thus solid conveying rate will be reduced.



- **Variable pitch extruder with increasing pitch:** Pitch increases with axial distance of the screw.
- The varying pitch allows the use of locally optimum helix angle, ie. Helix angle for solid conveying and helix angle for melt conveying.
- Used for high sensitive material. As well as power consumption is reduced by increasing the helix angle.
- Negative side is deflection of screw is more.



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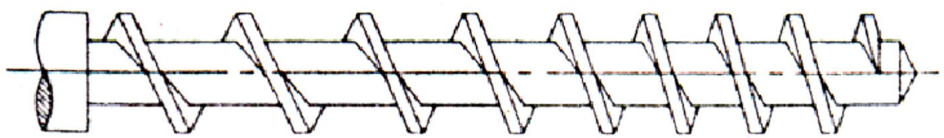
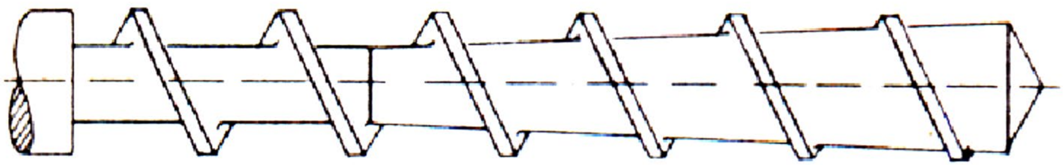
MODIFICATIONS OF SCREW

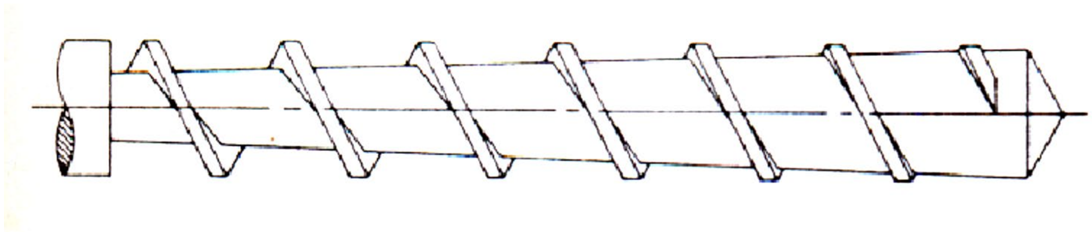
- **Variable pitch screw with reducing pitch:** Pitch decreased with axial distance.
- It causes a lateral compression of the material in the screw channel, so normal compression in the screw is eliminated.
- Same channel depth throughout the entire length of the screw.
- Negative side is reducing the helix angle, so increases the power consumption.
- It works on high clearance b/w flight and barrel, hence it reduces the melting capacity.

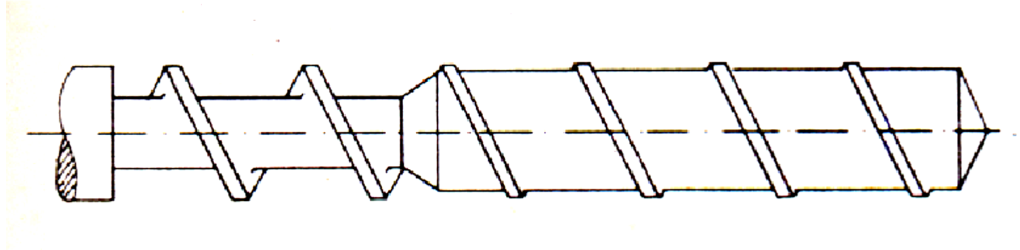


- **Zero meter screw:** Used to reduce the temp. build up in the material.
- Disadvantage is pressure generating capability of the screw will be affected. (not a major concern in the injection molding)
- It is more appropriate for an injection molding machine.
- 

• MODIFICATIONS OF SCREW

- **Zero feed Zero meter screw:** It consists of only a compression section.
- Hence gradual compression of the material takes place.
- Used especially for Nylon processing.



- **Rapid compression screw:** Length of compression zone is generally less than 1D in these screws.
- Unfortunately, it is referred to as Nylon screw.
- This is a major misconception in screw design and the success of zero feed zero meter with nylon should make that quite clear.
- Nylon has a narrow melting range and relatively low viscosity.
- 

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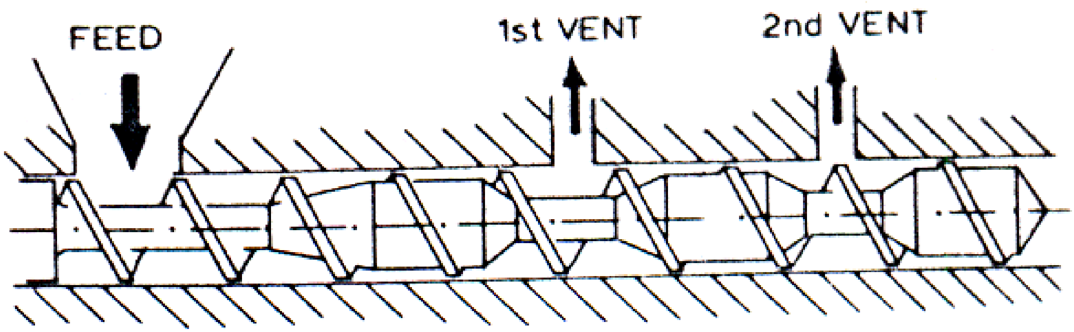
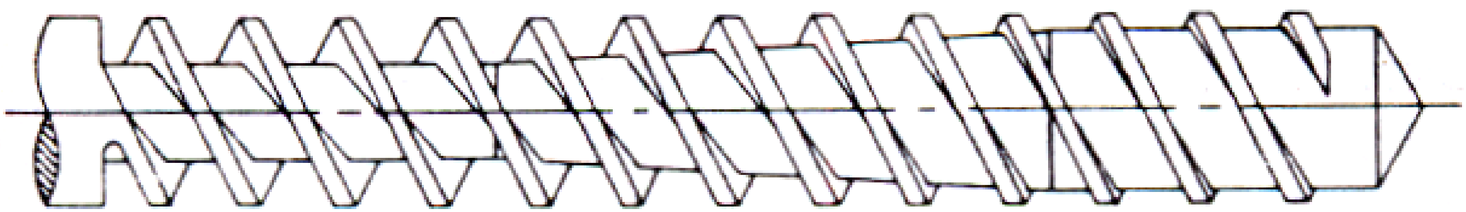
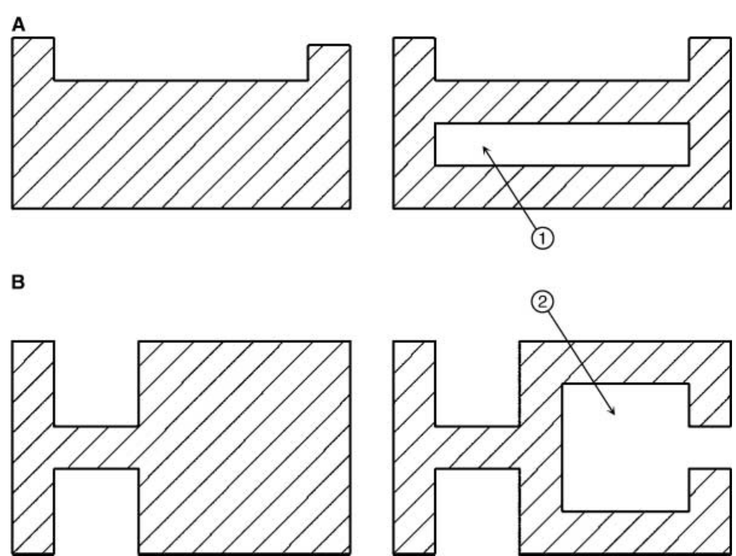
• MODIFICATIONS OF SCREW

- **Devolatizing extruder screw:** Used to extract volatiles from the polymer.



MODIFICATIONS OF SCREW

- **Multi-flighted screw:** Increase the melting performance.
- Reduce the screw deflection.
- Adversely affects the solid conveying and melt conveying rate, so multiple flights to be incorporated only a particular section of the screw.
- Negative side is power consumption is more.
- 
- 

• EXTRUSION – TROUBLESHOOTING

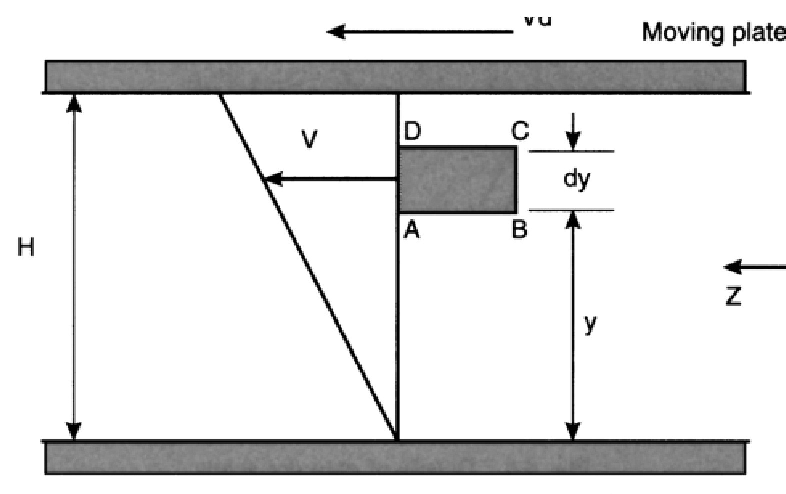
Problems	Possible Causes
Bubbles	• Localized hot spot in die • Material build-up in die • Improper screw design • Contamination in material
Bubbles uniformly distributed through extrudate	• High moisture content • Melt temperature too high • Improper screw design (excessive shear) • Incompatible additive • Die temperature too high
Melt fracture	• Metering depth too shallow • Metering depth too deep • Feed insufficient • Die land too short
Rough surface	• Improper screw design • Incompatible additive • Die temperature too low • Die land too long • High moisture content • Melt temperature too low

EXTRUSION – TROUBLESHOOTING

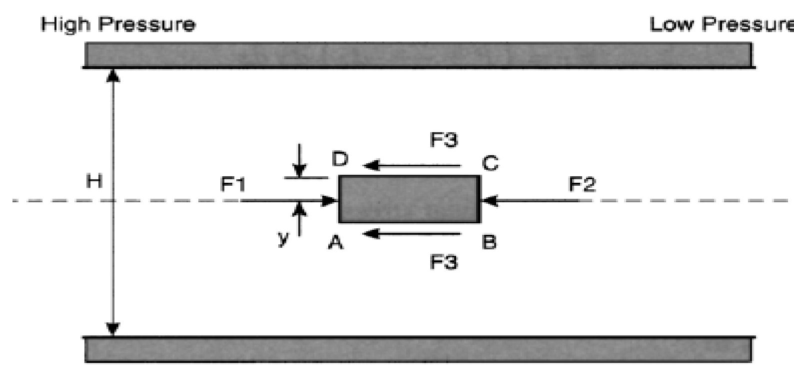
Problems	Possible Causes
Flow lines	• Melt temperature too low • Extruder output excessive • Poor mixing • Dirty extruder or die • Improper screw design • Die temperature too low • Back pressure too low • Extruder surging
Bridging in feed zone	• Screw overheated • Screw speed too low • Hopper dryer temperature too high • Rear zone temperature too high • Poor shut down procedure
Poor gauge control	• Takeoff variable • Temperature control inadequate • High moisture content
Carbon specks	• Dirty equipment • Improper resin handling • Extruder run dry at shut down and not cooled

- **Analysis of Flow in Extruder**
- The output from the extruder as consisting of three components - drag flow, pressure flow and leakage.
- The derivation of the equation for output assumes that in the metering zone the melt has a constant viscosity and its flow is isothermal in a wide shallow channel. These conditions are most likely to be approached in the metering zone.
- **(a) Drag Flow:** Consider the flow of the melt between parallel plates.
- For the small element of fluid ABCD the volume flow rate ***dQ is given by***
- $dQ = V * dy * dx$ *(4.1)*
- Assuming the velocity gradient is linear, then

$$V = V_d \left[\frac{y}{H} \right]$$



(a) Drag Flow



(b) Pressure Flow

In both cases, $AB = dz$, element width = dx and channel width = T

Fig. 4.7 Melt Flow between parallel plates

• Analysis of Flow in Extruder

Substituting in (4.1) and integrating over the channel depth, H, then the total drag flow, Q_d, is given by

$$Q_d = \int_0^H \int_0^T \frac{V_d y}{H} \cdot dy \cdot dx$$

$$Q_d = \tfrac{1}{2} T H V_d \qquad (4.2)$$

Fig. **4.8 shows** the position of the element of fluid and **(4.2) may be modified to include terms** relevant to the extruder dimensions.

For example ***Vd = πDNCOSϕ***

where *N is the screw speed (in revolutions per unit time).*

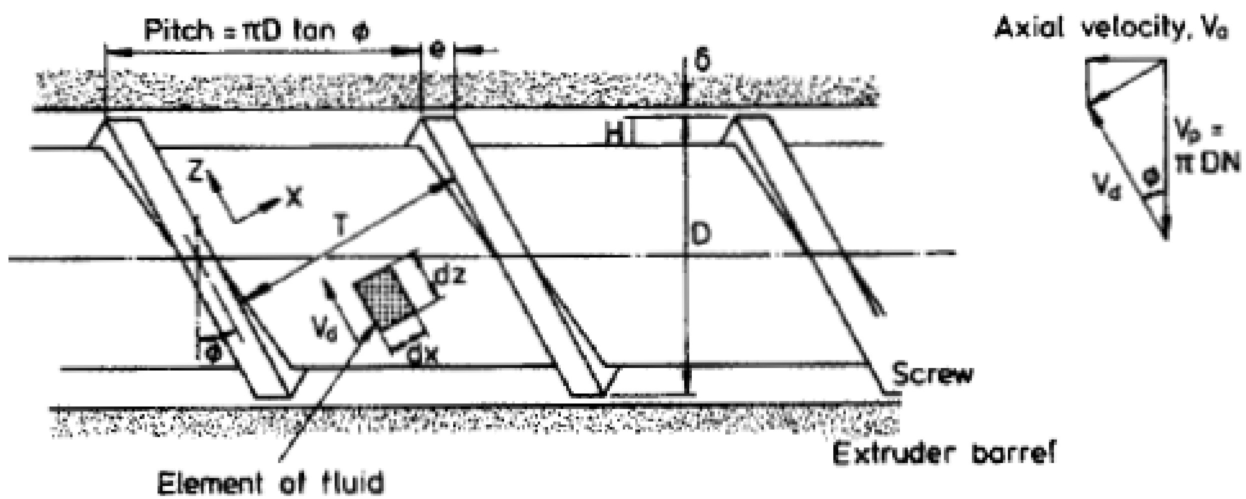


Fig. 4.8 Details of extruder screw

- # Analysis of Flow in Extruder

$$T = (\pi D \tan\phi - e)\cos\phi$$

So

$$Q_d = \tfrac{1}{2}(\pi D \tan\phi - e)(\pi D N \cos^2\phi)H$$

In most cases the term, e, is small in comparison with $(\pi D \tan\phi)$ so this expression is reduced to

$$Q_d = \tfrac{1}{2}\pi^2 D^2 N H \sin\phi\cos\phi \tag{4.3}$$

(b) Pressure flow: Consider the element of fluid shown in Fig. 4.7(b). The forces are

$$F_1 = \left(P + \frac{\partial P}{\partial z}\cdot dz\right) dy\, dx$$

$$F_2 = P \cdot dy\, dx$$

$$F_3 = \tau_y\, dz\, dx$$

where P is pressure and $d\tau$ is the shear stress acting on the element. For steady flow these forces are in equilibrium so they may be equated as follows:

$$F_1 = F_2 + 2F_3$$

$$y\frac{dP}{dz} = \tau_y$$

• Analysis of Flow in Extruder

Now for a Newtonian fluid, the shear stress, τ_y, is related to the viscosity, η, and the shear rate, $\dot{\gamma}$, by the equation

$$\tau_y = \eta\dot{\gamma} = \eta\frac{dV}{dy}$$

Using this in equation (4.4)

$$y\frac{dP}{dz} = \eta\frac{dV}{dy}$$

Integrating

$$\int_0^V dV = \frac{1}{\eta}\frac{dP}{dz}\int_{H/2}^{y} y\,dy$$

So

$$V = \frac{1}{\eta}\frac{dp}{dz}\left(\frac{y^2}{2} - \frac{H^2}{8}\right) \tag{4.5}$$

Also, for the element of fluid of depth, dy, at distance, y, from the centre line (and whose velocity is V) the elemental flow rate, dQ, is given by

$$dQ = VT\,dy$$

This may be integrated to give the pressure flow, Q_p

$$Q_p = 2\int_0^{H/2} \frac{1}{\eta}\frac{dP}{dz}\cdot T\left(\frac{y^2}{2} - \frac{H^2}{8}\right) dy$$

$$Q_p = -\frac{1}{12\eta}\frac{dP}{dz}\cdot TH^3 \qquad (4.6)$$

Referring to the element of fluid between the screw flights as shown in Fig. 4.8, this equation may be rearranged using the following substitutions. Assuming e is small, $T = \pi D \tan\phi \cdot \cos\phi$

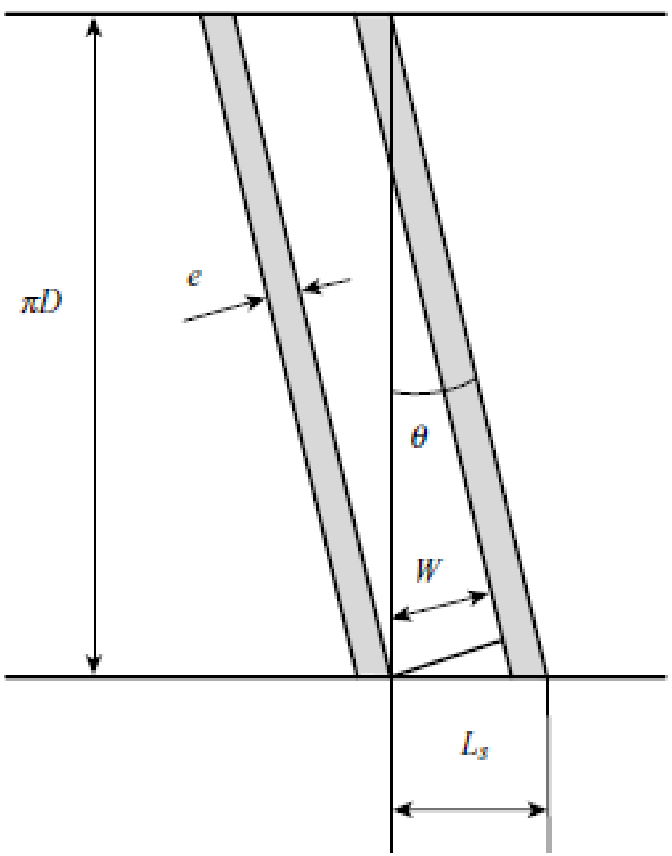
Also, $$\sin\phi = \frac{dL}{dz} \text{ so } \frac{dP}{dz} = \frac{dP}{dL}\sin\phi$$

Thus the expression for Q_p becomes

$$Q_p = -\frac{\pi D H^3 \sin^2\phi}{12\eta}\cdot\frac{dP}{dL} \qquad (4.7)$$

- The helical distance along the channel z is related to the axial distance L.

$$z = \frac{l}{\sin\theta}$$



• Analysis of Flow in Extruder

(c) Leakage The leakage flow may be considered as flow through a wide slit which has a depth, δ, a length $(e\cos\phi)$ and a width of $(\pi D/\cos\phi)$. Since this is a pressure flow, the derivation is similar to that described in (b). For convenience therefore the following substitutions may be made in (4.6).

$$h = \delta$$

$$T = \pi D/\cos\phi$$

$$\text{Pressure gradient} = \frac{\Delta P}{e\cos\phi} \text{ (see Fig. 4.9)}$$

So the leakage flow, Q_L, is given by

$$Q_L = \frac{\pi^2 D^2 \delta^3}{12\eta e} \tan\phi \frac{dP}{dL} \tag{4.8}$$

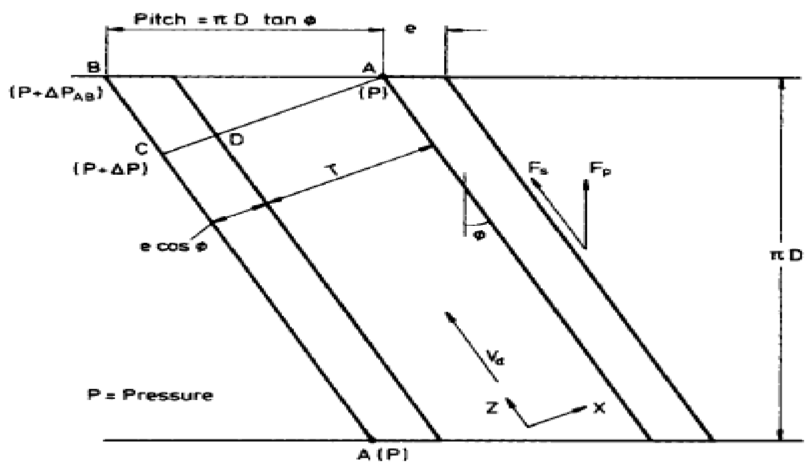


Fig. 4.9 Development of screw

- # Analysis of Flow in Extruder

The total output is the combination of drag flow, back pressure flow and leakage. So from (4.3), (4.7) and (4.8)

$$Q = \tfrac{1}{2}\pi^2 D^2 \text{ NH } \sin\phi\cos\phi - \frac{\pi D H^3 \sin^2\phi}{12\eta}\frac{dP}{dL} - \frac{\pi^2 D^2 \delta^3}{12\eta e}\tan\phi\frac{dP}{dL} \tag{4.9}$$

For many practical purposes sufficient accuracy is obtained by neglecting the leakage flow term. In addition the pressure gradient is often considered as linear so

$$\frac{dP}{dL} = \frac{P}{L}$$

From equation (4.9) it may be seen that there are two interesting situations to consider. One is the case of free discharge where there is no pressure build up at the end of the extruder so

$$Q = Q_{\text{max}} = \tfrac{1}{2}\pi^2 D^2 N H \sin\phi\cos\phi \tag{4.10}$$

The other case is where the pressure at the end of the extruder is large enough to stop the output. From (4.9) with $Q = 0$ and ignoring the leakage flow

$$P = P_{\text{max}} = \frac{6\pi D L N \eta}{H^2 \tan\phi} \tag{4.11}$$

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• Analysis of Flow in Extruder

•The output, ***Q,*** of a Newtonian fluid from a die is given by a relation of the form

$$Q = KP \qquad (4.12)$$

where $K = \dfrac{\pi R^4}{8\eta L_d}$ for a capillary die of radius R and length L_d.

Equation (4.12) enables the die characteristics to be plotted on Fig. 4.12

The operating point for an extruder/die combination may also be determined from equations (4.9) and (4.12) – ignoring leakage flow

$$Q = \tfrac{1}{2}\pi^2 D^2 NH \sin\phi\cos\phi - \frac{\pi D H^3 \sin^2\phi}{12\eta}\frac{P}{L} = \frac{\pi R^4}{8\eta L_d}\cdot P$$

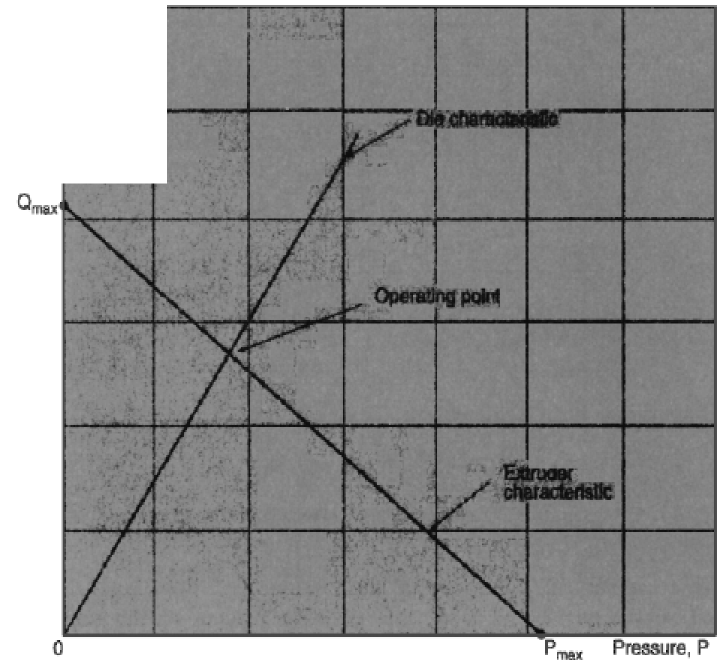

Fig. 4.12 Extruder and die characteristics

- **Analysis of Flow in Extruder**

Example 4.1 A single screw extruder is to be designed with the following characteristics.

L/D ratio = 24, screw flight angle = 17.7°
Max. screw speed = 100 rev/min, screw diameter = 40 mm
flight depth (metering zone) = 3 mm.

If the extruder is to be used to process polymer melts with a maximum melt viscosity of 500 Ns/m^2, calculate a suitable wall thickness for the extruder barrel based on the von Mises yield criterion. The tensile yield stress for the barrel metal is 925 MN/m^2 and a factor of safety of 2.5 should be used.

Solution The maximum pressure which occurs in the extruder barrel is when there is no output. Therefore the design needs to consider this worst case blockage situation. As given by equation (4.11)

$$P_{max} = \frac{6\pi D L \eta}{H^2 \tan \phi}$$

$$= \frac{6\pi \times 40 \times (24 \times 10) \times (100/60) \times 500}{(3)^2 \tan 17.7^0} = 210 \text{ MN/m}^2$$

The von Mises criterion relates the tensile yield stress of a material to a state of multi-axial stress in a component made from the material. In a cylinder (the

• Analysis of Flow in Extruder

barrel of the extruder in this case), the principal stresses which exist as a result of an internal pressure are

$$\text{hoop stress, } \sigma_1 = \frac{P_{\max} D}{2h}$$

$$\text{axial stress, } \sigma_2 = \frac{P_{\max} D}{4h}$$

where h = wall thickness of the barrel.

The von Mises criterion simply states that yielding (failure) will occur if

$$\left(\frac{\sigma_Y}{FS}\right)^2 \leq \sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2$$

where σ_Y = tensile yield stress of material

FS = factor of safety.

In this case, therefore

$$\left(\frac{925}{2.5}\right)^2 = \left(\frac{(210)40}{2h}\right)^2 + \left(\frac{(210)40}{4h}\right)^2 - \frac{(210)^2(40)^2}{8h^2}$$

$$h = 9.8 \text{ mm}$$

Hence a barrel wall thickness of 10 mm would be appropriate.

- **Analysis of Flow in Extruder**

Example 4.2 A single screw extruder is to be used to manufacture a nylon rod 5 mm in diameter at a production rate of 1.5 m/min. Using the following information, calculate the required screw speed.

Nylon	*Extruder*	*Die*
Viscosity $= 42.0\ \text{Ns/m}^2$	Diameter $= 30\ \text{mm}$	Length $= 4\ \text{mm}$
Density (solid) $= 1140\ \text{kg/m}^3$	Length $= 750\ \text{mm}$	Diameter $= 5\ \text{mm}$
Density (melt) $= 790\ \text{kg/m}^3$	Screw flight angle $= 17.7°$	
	Metering channel depth $= 2.5\ \text{mm}$	

Die swelling effects may be ignored and the melt viscosity can be assumed to be constant.

Solution The output rate of solid rod = speed × cross-sectional area

$$= 1.5 \times \pi(2.5 \times 10^{-3})^2/60$$

$$= 49.1 \times 10^{-6}\ \text{m}^3/\text{s}$$

As the solid material is more dense than the melt, the melt flow rate must be greater in the ratio of the solid/melt densities. Therefore

$$\text{Melt flow rate through die} = 49.1 \times 10^{-6}\left(\frac{1140}{790}\right) = 70.8 \times 10^{-6}\ \text{m}^3/\text{s}$$

• Analysis of Flow in Extruder

The pressure necessary to achieve this flow rate through the die is obtained from

$$Q = \frac{\pi P R^4}{8 \eta L_d}$$

$$P = \frac{8 \times 420 \times 4 \times 10^{-3} \times 70.8 \times 10^{-6}}{\pi (2.5 \times 10^{-3})^4} = 7.8 \text{ MN/m}^2$$

At the operating point, the die output and the extruder output will be the same. Hence

$$Q = 70.8 \times 10^{-6} = \tfrac{1}{2}\pi^2 (30 \times 10^{-3})^2 N (2.5 \times 10^{-3}) \sin 17.7 \cos 17.7$$

$$- \frac{\pi (30 \times 10^{-3})(2.6 \times 10^{-3})^3 \sin 17}{12 \times 420} \left(\frac{7.8 \times 10^6}{0.75} \right)$$

$$N = 22 \text{ rev/min}$$