**Extrusion Outline**

- definitions, concepts and products
- description of the extruders
  - continuous process
    - functions include melting, mixing and pressure generation
  - description of the parts
  - sizes of extruders
  - power requirements
  - resin feed system (hopper / dryer)
  - heating and cooling of the barrel
  - screw design
- discussion on dies
  - flow of Newtonian fluids through channels
  - die characteristics
- analysis of the extrusion process
  - description of the melting process
  - description of the pumping capability
  - analysis of heat needed
- some sample problems in extrusion
- description of some extrusion processes
  - pipe extrusion
  - wire coating
  - blown film extrusion
- problems encountered during extrusion
  - die swell
  - shear heating
  - melt fracture
  - sag
This section covers the basics of extrusion. There are many products made via extrusion and most of them involve machinery for melting the plastic (an extruder) and the means to shape the plastic melt (a die).

So the processing steps involved in extrusion are:

- **melting** (add heat to the polymer)
- **mixing and homogenization of the melt** (not covered here)
- **pumping** (transport of the melt)
  - this can be accomplished by generating melt at a high pressure or by using an actual pump (like a gear pump)
- **forming** (shaping the melt)
- **cooling** (remove excess heat so that the material becomes rigid and retains its shape)

Extruded products include:

- **films for packaging**  
  - barrier (gas, moisture)
- **plastic pipe and tubing**  
  - rigid conduit
- **insulation for wiring**  
  - insulation (electrical)
- **filaments for rope, line, fibers**  
  - tensile properties
- **coated paper**  
  - barrier (moisture)
- **sheet products for signs, lighting panels**  
  - rigidity
- **profiles for house siding,**  
  - rigidity
- **gaskets (as on a refrigerator door)**  
  - elastic properties
  - (to enhance seal)
The Hardware

Sketch of Extrusion Line

Note: this is a continuous process

To pump molten plastic through the die, it is necessary to develop a pressure in the melt.

- we have the flow of a very viscous fluid through a channel

Thus the function of the extruder is to:

- melt the plastic
- pump the plastic (generate a pressure which can be as high as 2000 psi)

both these functions are very important

i.e. the extruder needs to supply a homogeneous molten material at a flow rate, temperature and pressure suitable for the next step in processing
Parts of an extruder

- hopper for feeding in materials, it can be preceded by a drying unit
- a barrel assembly (usually steel)
- with a screw inside (used to push the plastic down the barrel, this also generates the melt pressure)
- a heating system consisting of
  - electric band heaters
  - thermocouples to monitor barrel temperatures
  - a control system to maintain temperature
- a drive system for the screw
  - electric motor
  - gear reducing assembly
  - speed control
- a die for shaping the product

Extruders are commonly sized according to two numbers.
• barrel inside diameter
e.g. 1", 1 1/2", 2", ...... 6"

• length of the extruder or L/D ratio
  20/1, 24/1, 28/1 being most common

Power requirements for the electric motor

• 1 hp per 5 to 10 lbs/hr of material

The flow rate through the extruder is almost directly proportional to the RPM (screw speed). If the RPM doubles, the flow rate doubles.

common screw speeds 20 to 200 RPM

Feeding in the Resin

Resin is usually fed into a hopper, a large funnel shaped container which sits on top of the extruder.

Resin flows into the extruder by gravity but feed screws (or augers) can be used to control the flow rate of resin into the system.

Sometimes there are screens or magnets in the hopper to remove metals and other contaminants.

Vibration of the hopper walls can be used to prevent solid bridging in the throat (the smallest section) of the hopper.

Some materials either absorb a lot of moisture when exposed to air or degrade in the melt state when exposed to moisture. These resins need to be dried before they are processed. So, often we will use a dehumidifying dryer to reduce the moisture levels in the resin before the resin is transported to the hopper.

The drying is accomplished by passing hot, dry air over the resin pellets.
Heating and Cooling System

- hopper / throat area is cooled to prevent material from becoming sticky and blocking the channel before the material feeds into the screw

- there are usually 3 to 5 heating zones along the barrel

- electric heaters are important for startup but after the process is running, heat generated by friction of the melt in the barrel supplies most of the heat (80% to 90%)

Some systems might even need cooling systems (e.g. air blowers)

It is important to control the melt temperature for the following reasons:

- avoid thermal degradation
- too high a temperature may make post extrusion processing difficult
- waste of energy
Screw Design

- helical channel for flow
- very small clearance between the screw flight and barrel
- depth of flow channel usually small compared to the screw diameter
- depth may vary along the channel
Generally 3 sections along the screw

- feed section - the deepest channel
  where solid pellets come into contact with the barrel wall
  heat of friction starts to melt the pellets

- metering section - shallowest channel depth
  melting is completed
  the melt is homogenized
  the pressure profile is built up

The thread of the screw is called a flight.
One design parameter is the pitch -- the distance from one flight to the next

A square pitch screw has a pitch = screw diameter
This results in a helical angle of 17.7°.
This is the most common design.

A second design parameter is the channel depth.
This varies from the feed section through the metering section.
e.g. from 3/8” to 1/8”

A third design parameter would be the L/D ratio.
The Die

The die in its simplest form is just a flow channel within a piece of metal. It can be a circular channel, a slit, or something much more complex.

Types of dies
- capillary dies (filaments, yarns)
- flat dies (sheet)
- dies to produce hollow tubes (pipe, films)
- profile dies (irregular cross sections)

Flow in a cylindrical channel

\[ V_z = V_{\text{max}} \left\{ 1 - \left(\frac{r}{R}\right)^2 \right\} \quad \text{Newtonian fluid} \]

\[ Q = \frac{\pi (\Delta P) R^4}{8 \eta L} \quad \text{capillary die flow} \quad (1) \]

where
- \( r \) - radial position
- \( R \) - radius of the channel
- \( L \) - length of the channel
- \( \Delta P \) - pressure drop over the channel
- \( \eta \) - viscosity
- \( Q \) - volumetric flow rate
- \( V_z \) - velocity
- \( V_{\text{max}} \) - maximum velocity
In general, for a Newtonian fluid we might express the behavior of the die as:

\[ Q = \frac{K (\Delta P)}{\eta} = K' \Delta P \tag{2} \]

where \( K \) is a function of the die geometry and \( \eta \) is the melt viscosity.

**Important**

The performance of an extruder is affected by the resistance to flow offered by the die. In general, we cannot separate extruder design from die design.

Problems in die design are concerned with:
- obtaining the desired shape (swell of polymer distorts the shape)
- " uniform thickness
- " uniform temperature
- avoiding surface defects
Analysis of Extruder Behavior

based on screw design

functional

Solid Bed

- mostly solid pellets
- friction between the pellets and barrel causes some pellets to melt and form a film
- when enough has melted, we start to see the formation of a melt pool
Melting

- Tadmor model - all the solids collect on one side of the channel, the melt on the other
- the gap between the top of the solid bed and the moving barrel is fairly small
- frictional heating in this gap produces much of the thermal energy to melt the resin
- model has been verified by experiment
Analysis of the Pumping Capacity of an Extruder

In the simplest approach, we can unwrap the channel from the screw to get a long channel with a rectangular cross section

Thus now we can treat this as flow in a slit (we are ignoring the effects of the flights)
There are two types of flow

- **drag flow** due to the motion of the screw in the barrel. This has a downstream component \((z)\) in the channel and a cross-stream component.

- **pressure flow** due to the pressure build-up along the channel

Note that since the pressure increases with distance down channel, that the flow due to the pressure gradient is in the opposite direction as that due to the drag flow.

The final relation is of the form:

\[
Q = \alpha N - \beta \frac{\Delta P}{\eta} \tag{3}
\]

where

- \(\alpha, \beta\) depend on the geometry
- \(N\) RPM of the screw
- \(\eta\) viscosity of the melt
- \(\Delta P\) pressure increase over the length of the screw

We have 1 equation and 2 unknowns to solve for \((\Delta P, Q)\)

We need a 2nd equation - this comes from the die.
(thus we are solving equations 2 & 3)
Graphically, the solutions look like:

For the extruder treated as a rectangular channel

\[ Q = \frac{WH}{2} \left\{ \pi D_s N \cos(\phi) - H^2 \frac{\Delta P}{6 \eta L_c} \right\} \]  

(4)

- \( N \) RPM of the screw
- \( \eta \) viscosity of the melt
- \( \Delta P \) pressure increase over the length of the screw
- \( W \) width of the channel
- \( H \) depth of the channel
- \( D_s \) diameter of the screw
- \( \phi \) helical angle
- \( L_c \) length of the channel

( Go over problem #1 ) - need to be careful of the computation of the channel length
Heat Needed for Melting

We also need to be concerned about the amount of heat required to melt the polymers

\[ \Delta H = \left[ C_p \Delta T + \lambda_f \right] \]

(5)

power required for a throughput of \( Q_m \) (e.g. kg/sec)

\[ P_T = Q_m \left[ C_p \Delta T + \lambda_f \right] \]

(6)

Typical values are:

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<th></th>
<th>( C_p ) (kJ/kg-°C)</th>
<th>( \lambda_f ) (kJ/kg)</th>
<th>process temp (°C)</th>
<th>( \rho_m ) (gm/cm(^3))</th>
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<td>290</td>
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</tbody>
</table>
**Description of Some Extrusion Processes**

**Pipe Extrusion**

usually use  
PE  
PVC  
ABS  
nylon

Cooling the pipe and controlling the size are the most important parts of the process.

For cooling often a water trough is used.

Plates with holes through which the tubing is drawn are often used for sizing
Wire Coating

One of the first uses of extruders

drawdown

multiple coating

7.27 Wire coating tubing die (after Richardson).
Blown Film Extrusion

air cooled

thickness uniformity is important

film width controlled by the amount of air in the bubble

7.2 Die, 'bubble', and take-off equipment in a film blowing unit.