POLYMER AND COMPOSITE MATERIALS PROCESSING

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Ch. 4. EXTRUSION

What is extrusion

- The extrusion process comprises the forcing of a plastic or molten material through a shaped die by means of pressure.
- The most widely used type is the single screw machine.
- Twin screw extruders are also used where superior mixing or conveying is important.
- Solid polymer is fed in at one end and the profiled molten extrudate emerges from the other.
- Inside, the polymer melts and homogenizes.

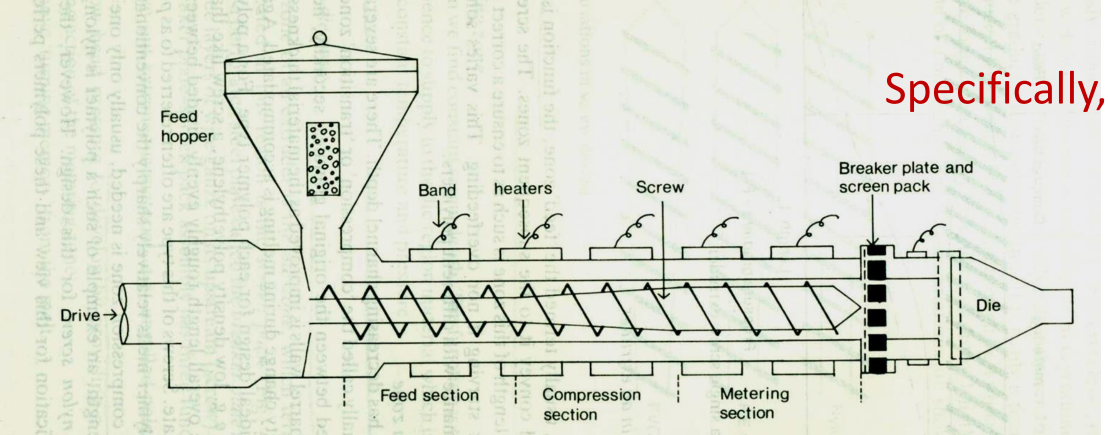


Fig. 4.1 Main features of a single screw extruder.

Specifically, blending or compounding?

Features of a single screw extruder

- The screw of an extruder has one or two flights spiralling along its length.
  - The diameter to the outside : constant along the length to allow the close fit in the barrel.
  - The root or core, however, is of varying diameter and so the spiralling channel varies in depth.
  - A consequence of the decreasing channel depth : increasing pressure along the extruder.

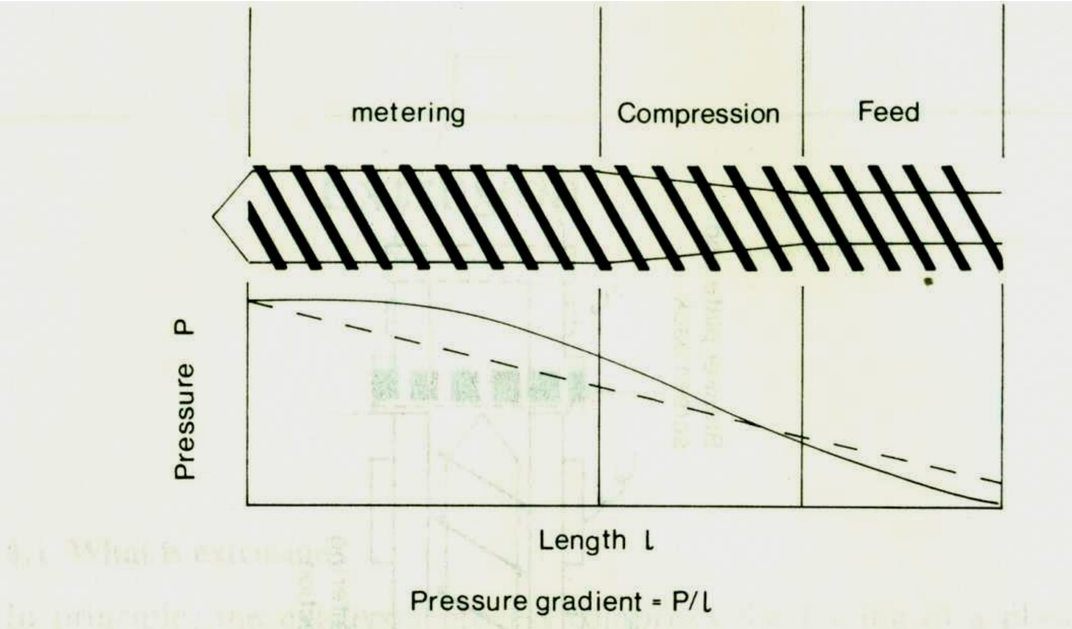
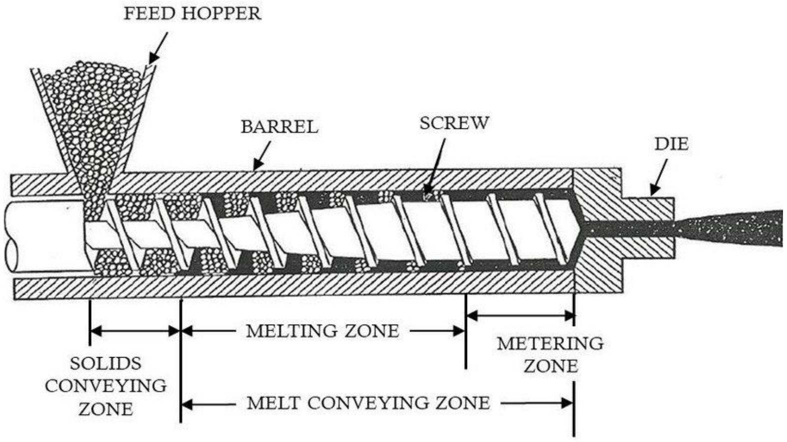


Fig. 4.2 Zones in a single screw extruder.



- The zones in an extruder

  1) Feed zone

  - Preheat the polymer and convey it to the subsequent zones.
  - The constant screw channel depth

  2) Compression zone (transition zone)

  - The decreasing channel depth
  - The several functions
    - It expels air trapped between the original granules
    - Heat transfer from the heated barrel walls is improved as the material thickness decreases.
    - The density change (high packing of materials) during melting is accommodated.

  3) Metering zone

  - The constant screw depth (pressure stabilized)
  - The function is to homogenize the melt and hence to supply to the die region.

4) The die zone

- The final zone = die zone :
  - To sieve out extraneous material, e.g. ungelled polymer, dirt, foreign bodies
  - To allow head pressure to develop by providing a resistance for the pumping action of the metering zone
  - To remove ‘turning memory’ form the melt : this is due to the viscoelastic behavior of polymers.

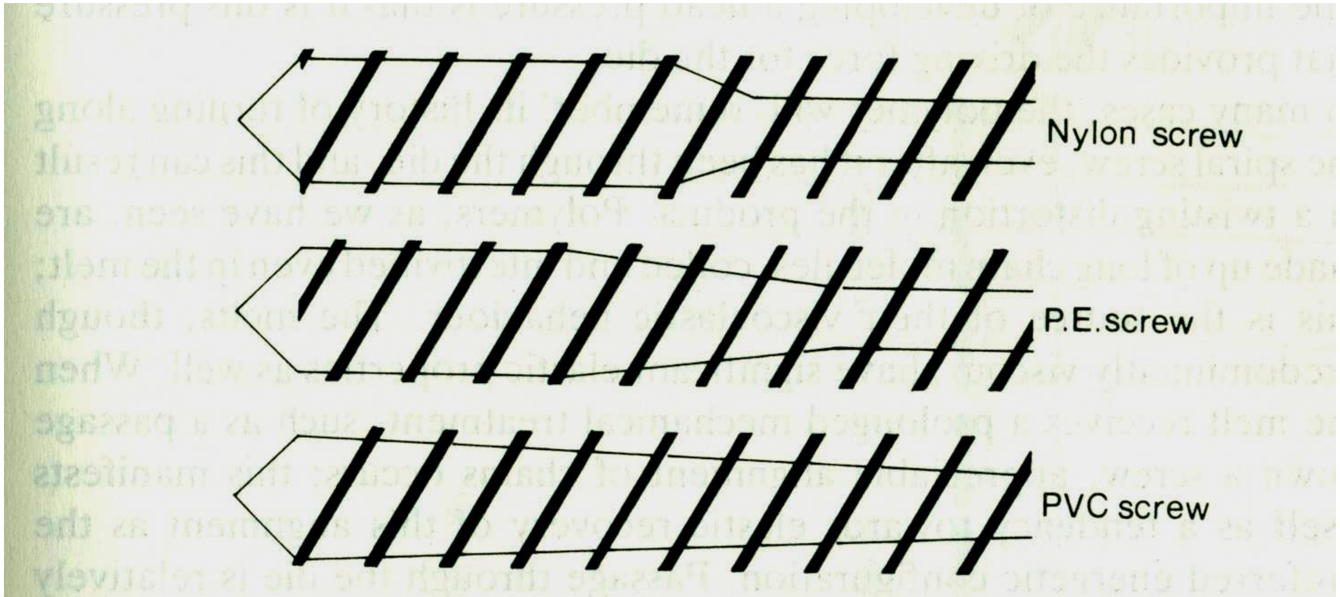
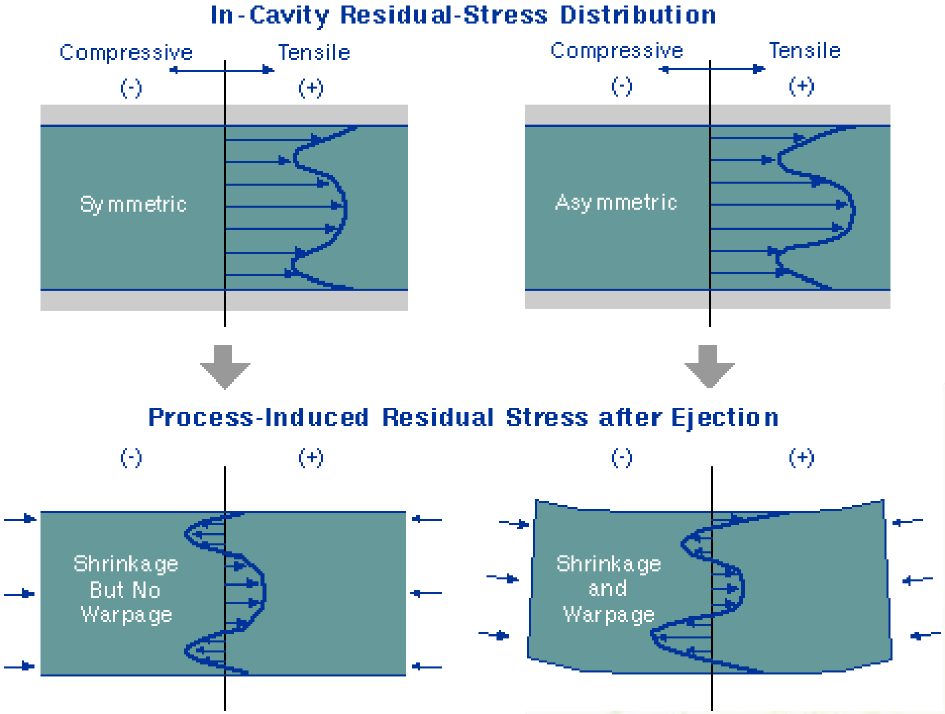


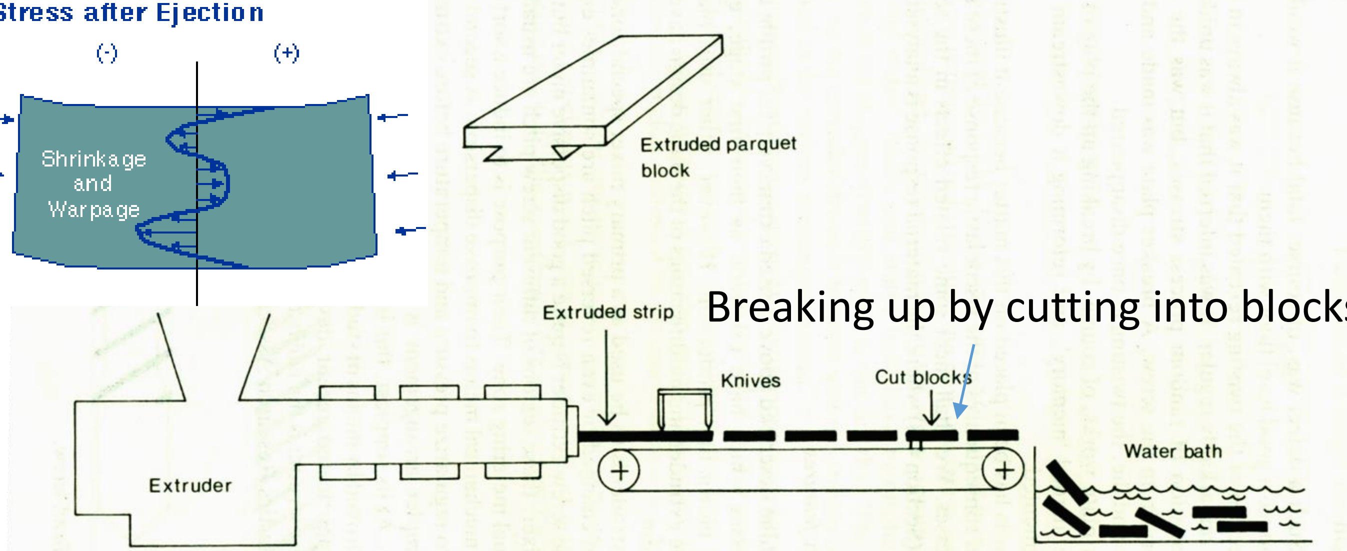
Fig. 4.3 Variations in screw design.

• An example of 'turning memory'

- When they were removed from the cooling bath, they were all twisted.

→ Why twisted? "Residual stress"

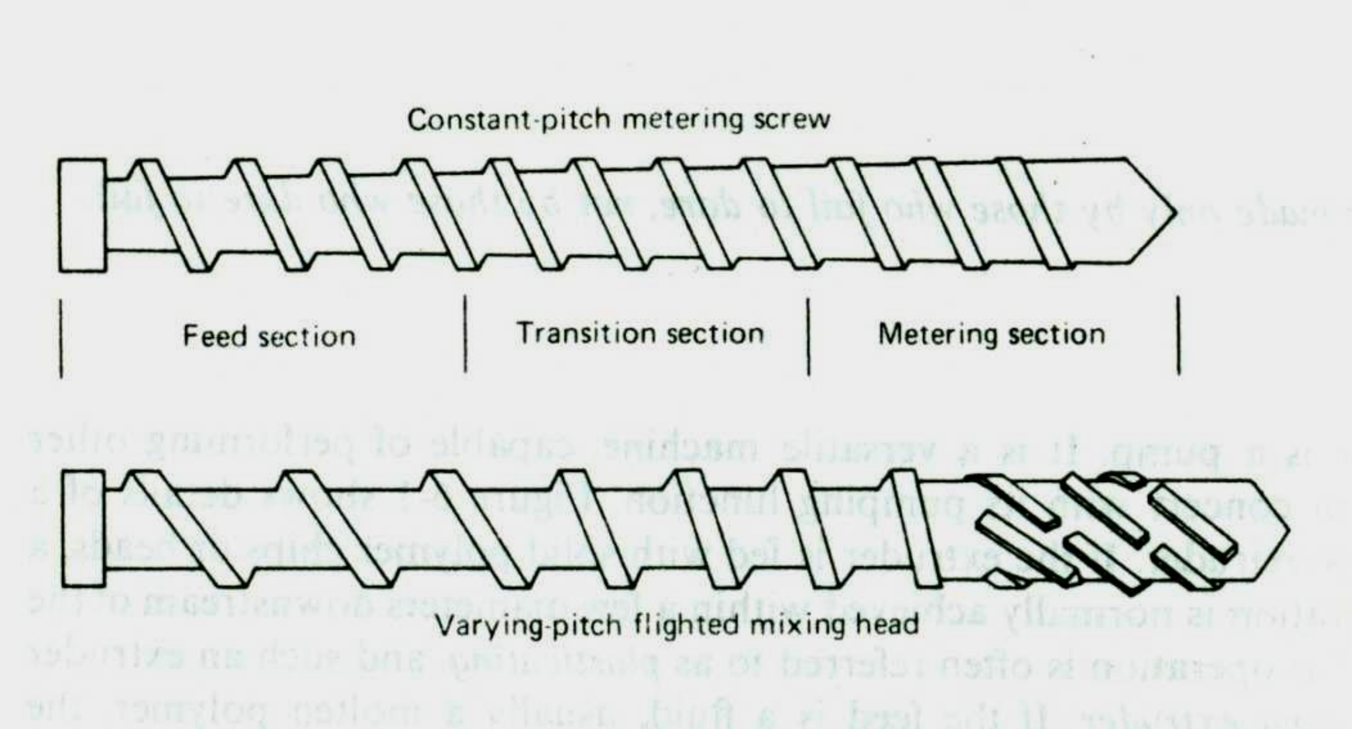




Breaking up by cutting into blocks

Fig. 4.4 Manufacture of parquet flooring blocks.

- Specialty features
  - The basic single screw extruder is quite a good dispersive mixer but is a poor distributive mixer.
  - special zones having screw flights of changed or even reversed pitch : it achieves a good distribution.



- Venting volatiles during extrusion: The screw has a decompression region, followed by recompression and a further metering zone.

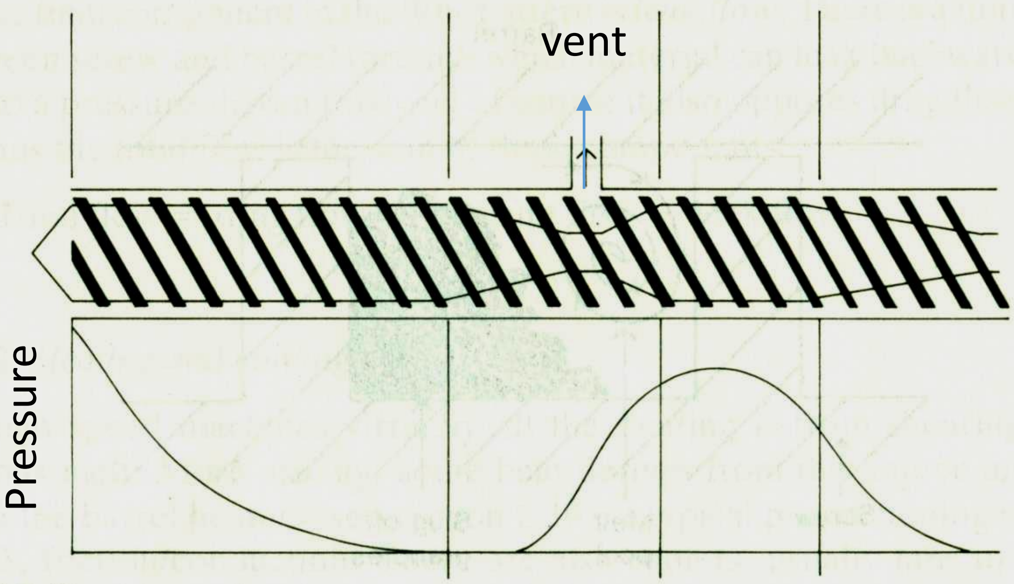


Fig. 4.7 Decompression zone.

Flow mechanisms

1) Melting

- As the polymer is conveyed along the screw, a thin film melts at the barrel wall.
- This is usually by means of conducted heat from the barrel heaters, but could be frictional.
- The molten polymer moves down the front face of the flight to the core and then sweeps up again to establish a rotary motion in front of the leading edge of the flight.

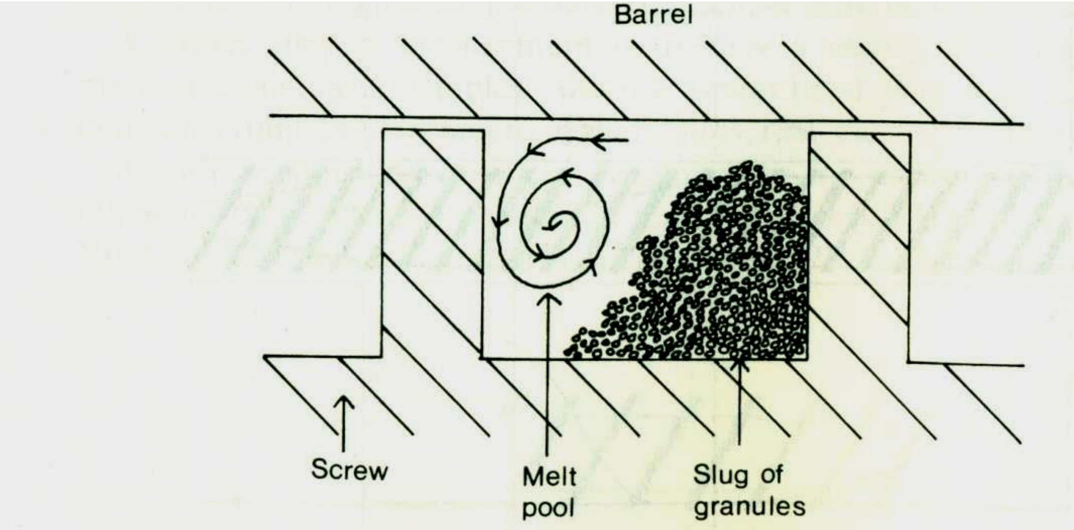
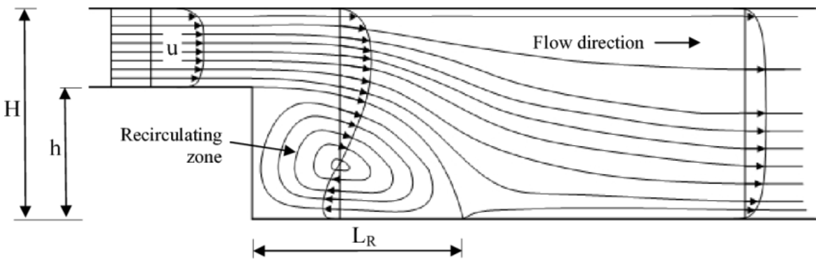


Fig. 4.8 The melting process.



2) Conveying (수지 이송)

- Two extreme cases : Poor dispersion and distribution
  - The material sticks to the screw only and slips on the barrel
    - The screw and material would simply rotates as a solid cylinder and there would be no transport.
  - The material resists rotation in the barrel and slips on the screw.
    - It will now tend to be transported axially.
- Drag flow
  - In practice, there is friction with both screw and barrel, and this leads to the principal transport mechanism, drag flow.
  - This is the equivalent to the viscous drag between stationary and moving plates separated by a viscous medium.

- Pressure flow
  - It is opposed by the pressure flow component, which is caused by the pressure gradient along the extruder
  - There is no actual flow resulting from the pressure.
- Leak flow
  - There is a finite space between screw and barrel through which material can leak backwards (backflow).
  - This is also a pressure-driven flow and of course it also opposes drag flow.

Total flow = Drag flow – Pressure flow – Leak flow

3) Heating and cooling

- More usually some heat derives from the viscous heating and some from the barrel heater.
  - A typical proportioning might be 67/33 , friction/conduction.
- There are also coolers, usually fans to remove excess heat. (cooling is not usual).

- Adiabatic (Q = 0) and isothermal (T = constant)
  - The practical running condition may be regarded as lying between the extremes of adiabatic running, when there would be only heat from viscous dissipation, and isothermal running, when the temperature at all points would be the same, with heat being supplied by heaters or removed by coolers to compensate for changes in melt temperature.

Analysis of flow

- Drag flow

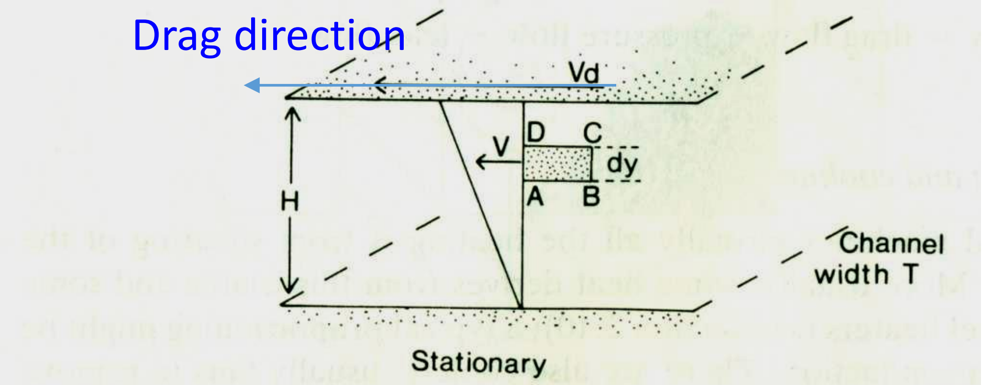


Fig. 4.9 Drag flow between parallel plates.

- The volume flow rate for this element, dQ

$$dQ = TVdy$$

- Assuming a linear velocity gradient,

$$V = \frac{V_d y}{H} \qquad dQ = \frac{TV_d ydy}{H}$$

- Integrate the above equation over the channel depth, H

$$Q_d = \int \frac{TV_d ydy}{H} = \frac{THV_d}{2}$$

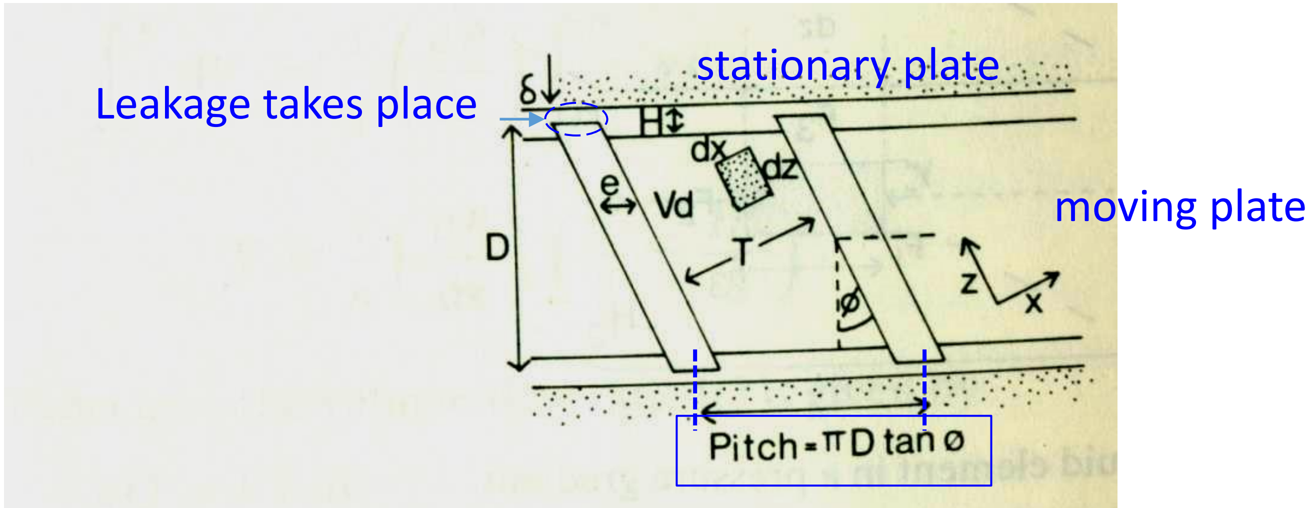


Fig. 4.10 Drag flow in an extruder screw.

- Application of the parallel plate to an extruder
  - The equivalent of the stationary plate is the barrel and of the moving plate is the rotating screw.

Drag velocity $V_d = \pi D N \cos\phi$ *N*: frequency of screw rotation (revolution/s)

Distance b/t screw $T = (\underbrace{\pi D \tan\phi}_{\text{pitch}} - e)\cos\phi$

Flow rate in drag flow $Q_d = \frac{THV_d}{2} = \frac{(\pi D \tan\varphi - e)(\pi D N \cos^2\varphi)H}{2} = \frac{\pi^2 D^2 N \sin\varphi \cos\varphi H}{2}$

: Flow rate driven by drag flow in a extruder
→ function of D, N, H, angle

- Drag flow depends on
  - Screw diameter
  - Screw speed
  - Channel depth
  - Helix angle
- The helix angle is almost universally fixed at the square angle of 17.66°, i.e. one turn per diameter's length of screw.

- Pressure flow

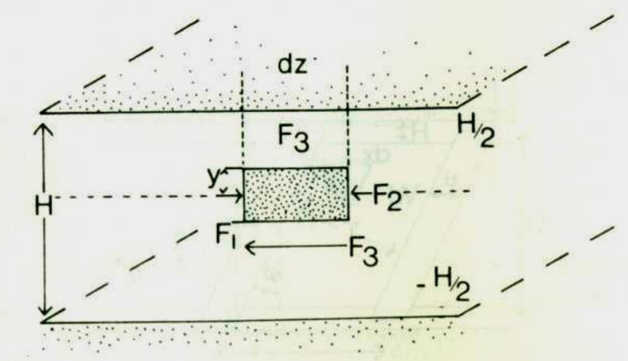


Fig. 4.11 Forces on a fluid element in a pressure gradient.

- The forces acting on the fluid element are, for unit width

$$F_1 = \left(P + \frac{\partial P}{\partial z} dz \right) 2y$$

$$F_2 = P2y \qquad F_3 = \tau dz$$

- During steady flow, these are in equilibrium

$$F_1 = F_2 + 2F_3$$

- We reduce the following equation:

$$\tau = y\frac{\partial P}{\partial z}$$

- Assuming a Newtonian fluid,

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

- After combining the two equations,

$$\eta\frac{dV}{dy} = y\frac{dP}{dz} \qquad \frac{dV}{dy} = \frac{1}{\eta}\frac{dP}{dz}y$$

- Now, we can take the integration,

$$V = \int_0^V dV = \frac{1}{\eta}\left(\frac{dP}{dz}\right)\int_{H/2}^{y} y\,dy = \frac{1}{\eta}\left(\frac{dP}{dz}\right)\left(\frac{y^2}{2} - \frac{H^2}{8}\right)$$

$$dQ = VTdy = \frac{1}{\eta}\left(\frac{dP}{dz}\right)\left(\frac{y^2}{2} - \frac{H^2}{8}\right)Tdy$$

$$Q_p = VT2y = 2\int_0^{H/2} \frac{1}{\eta}\left(\frac{dP}{dz}\right)\left(\frac{y^2}{2} - \frac{H^2}{8}\right)Tdy = \left(\frac{1}{12\eta}\right)\left(\frac{dP}{dz}\right)TH^3$$

- When applying this expression to an extruder screw channel,

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

$$\sin\phi = \frac{dl}{dz}$$

- Then, $$\frac{dP}{dz} = \left(\frac{dP}{dl}\right)\sin\phi$$

$$Q_p = \left(\frac{\pi D H^3 \sin^2\phi}{12\eta}\right)\left(\frac{dP}{dl}\right)$$

~ *P* / *l* for linear change

: Flow rate driven by pressure in a extruder

→ function of *H*, *D*, *viscosity*, *and pressure gradient dP/dl*

- Leak flow
  - Leak flow is another pressure driven flow component.
  - The geometry is that of a wide slit;
    - $H=\delta$, the depth of the slit
    - $T=\pi D/\cos\phi$, the width of the slit
  - Leak flow is small compared with drag flow and pressure flow and may be neglected in finding total flow.
  - It only has practical significance in badly worn machines where the clearance between screw and barrel becomes large.

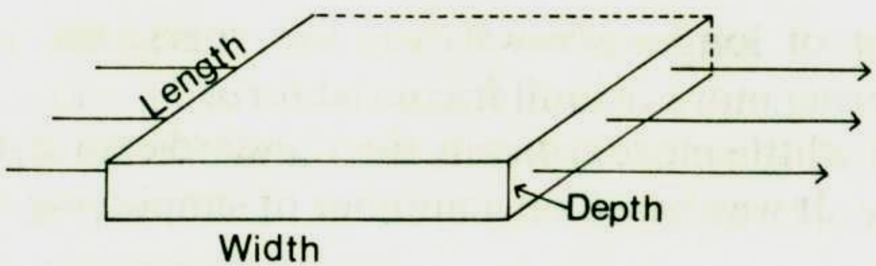


Fig. 4.12 Leak flow through a wide slit.

- Total flow

$$Q = Q_d - Q_p = \frac{\pi^2 D^2 NH \sin\phi \cos\phi}{2} - \left(\frac{\pi DH^3 \sin^2\phi P}{12\eta l}\right)$$

- For practical purpose,

$$Q = \alpha N - \left(\frac{\beta P}{\eta}\right)$$

- The practical variables
  - Screw speed *N*
  - Head pressure *P*
  - Melt viscosity η
  - Screw design $\alpha, \beta = f(\phi, D, H)$

- Influence of polymer properties
  - The two important factors missing are (a) the non-Newtonian rheology of most polymer melts and (b) their frictional properties.
  - The frictional drag at the barrel prevents the melt from simply rotating with the screw.
  - In fact, the polymeric material must slide on the surfaces and the sliding characteristics are described by the relevant coefficients of friction.

Table 4.1 Coefficients of friction, various countersurfaces

Polymer	*Coefficient of friction (λ)*
PTFE	0.04–0.15
LDPE	0.30–0.80
HDPE	0.08–0.20
PP	0.67
PS	0.33–0.50
PMMA	0.25–0.50
Nylon	0.15–0.40
PVC	0.20–0.90
SBR	0.50–3.0
NR	0.50–3.0

After Hall [4].

High friction ? → good drag flow (prevent simply rotating with the screw)

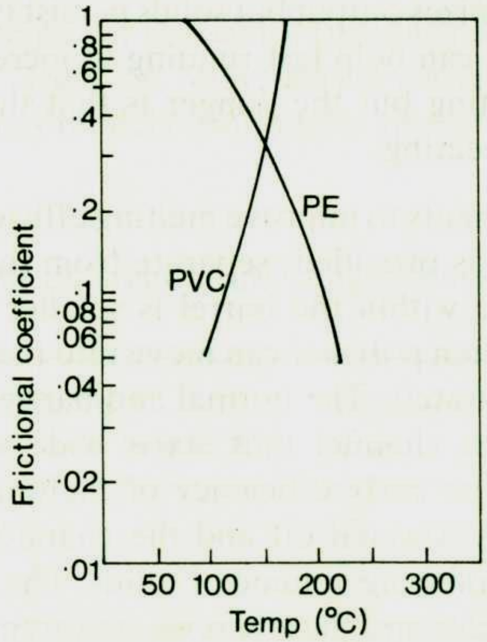


Fig. 4.13 Comparison of frictional properties of polyethylene and PVC (after Jacobi).

- PVC is a polymer notorious for thermal instability.
- Thus, it is a difficult polymer to run in a single screw extruder, is more often extruded in twin screw machine.

→ This is the reason twin screw extruder is used for many polymer melts.

Some aspects of screw design

- Two important aspects
  - The efficiency of melting and the output rating of the extruder
- Melting efficiency
  - Some variations in screw characteristics
    - Deeper channel
      - Conveys more material but takes longer to complete melting
    - Fast running
      - Maximizes output but solids persist further along the screw
    - Shallower channel
      - Can help fast running to increase output because of more efficient melting but the danger is that the resultant high shear might lead to overheating.

- Optimum helix angle
  - The competing requirements are a steep angle to resist back pressure flow and a shallow angle to provide the least tortuous path <u>for drag flow</u>.

Steep helix angle
(prevent back pressure flow)

Shallow helix angle
(bad drag flow efficiency)

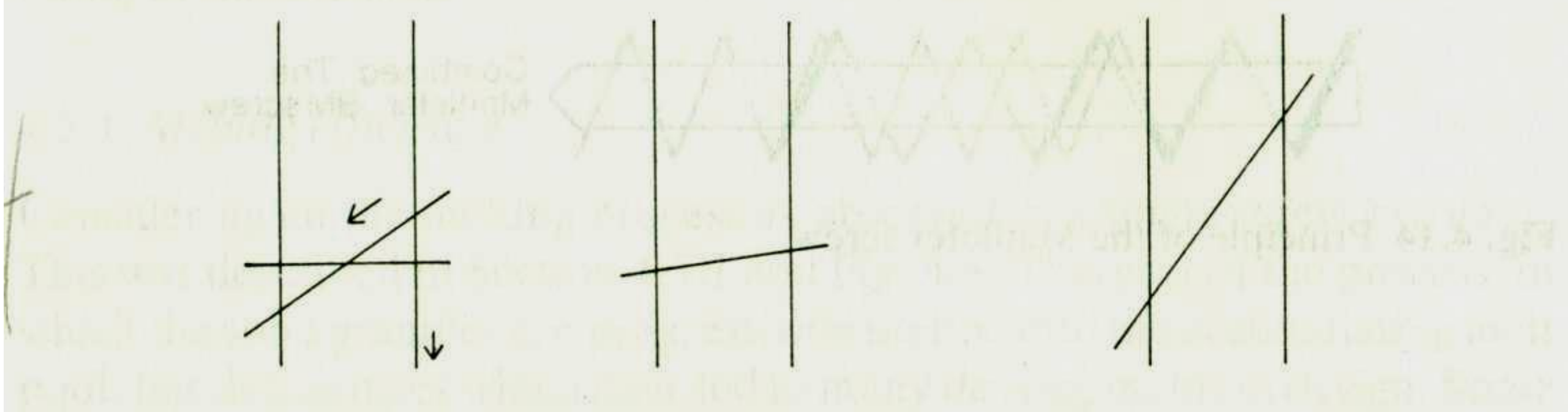
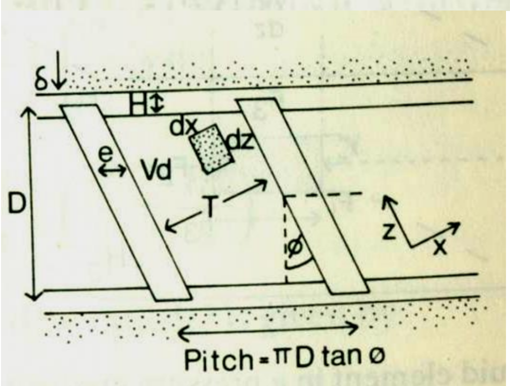


Fig. 4.15 Steep vs. shallow helix angle: the steep angle resists back pressure flow; the shallow angle provides least tortuous drag flow path.



Remember this angle ϕ direction:

- Perpendicular to barrel : $\phi = 0$ → blocked
- Parallel to barrel : $\phi = 90$ → No head pressure

- The volumetric efficiency, at least of drag flow, depends only on ϕ.

- The 'ideal' axial velocity (= velocity along the barrel direction)

$$V_a = \text{screw picth x screw speed} = \pi D tan\phi \times N$$

- The velocity component parallel to the screw flight (screw 나사선 방향)

$$V_d = \frac{V_a}{sin\phi} = \frac{\pi D N tan\phi}{sin\phi}$$

- The 'ideal' output (flow rate): $Q_i = V_d \times \text{crosssection of channel}$

$$Q_i = \frac{\pi D N tan\phi}{sin\phi}(\pi D H tan\phi)cos\phi = \pi^2 D^2 H N tan\phi$$

Maximum flow rate by drag flow we learned!

$$\therefore \text{Volumetric efficiency} = \frac{Q_{max}}{Q_i} = \frac{(\frac{1}{2})\pi^2 D^2 N \sin\varphi \cos\varphi H}{\pi^2 D^2 H N tan\phi} = \frac{1}{2} cos^2\phi$$

e.g. Angle of 17.66° gives an efficiency of 45.4%.

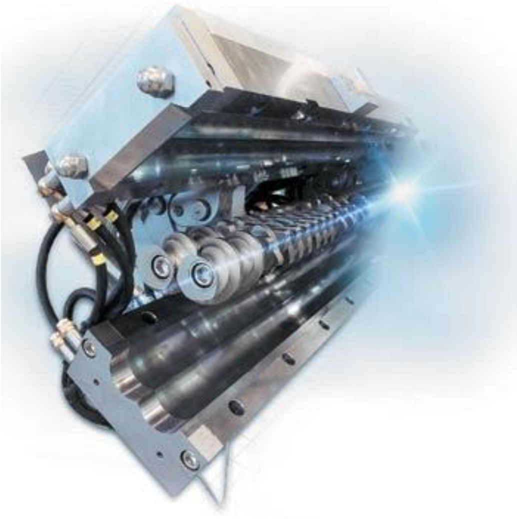
Angle of 10° gives rises to only 48.5%

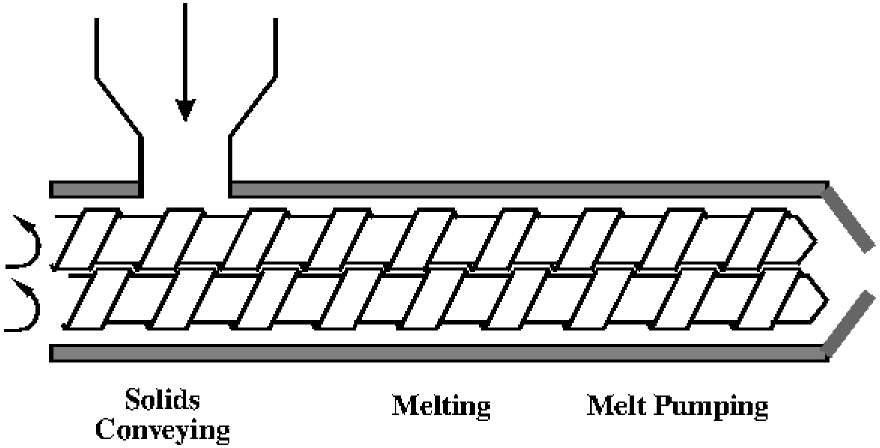
→ Helix angle shouldn't be too steep!

→ Universally accepted value = 17.66 °

Twin screw extruder

- PVC
  - Heat sensitive polymer
  - One of the applications is extrusion of window frames and associated products, e.g. frames for patio doors, main house doors, etc., in unplasticized or rigid PVC.





- Melt conveying in twin-screw extruders
    - Twin-screw extruders act as positive displacement pumps with little dependence on friction, and this is the main reason for their choice for heat sensitive materials.

- Categories of twin-screw extruders
  - The first division depending on the rotating direction
    - Co-rotating
    - Counter-rotating
  - The second division depending on whether the two screws mesh with each other or not
    - Meshing
    - Non-meshing
      - Double screws

Extruder and die characteristics

- The interaction of the extruder and its die can be understood by looking at their respective characteristics.
- If there were to be no pressure build-up, for example, no breaker plate or die, the output would be at its maximum.
  - We can use the drag flow ideal equation.

$$Q = Q_{\max} = \frac{\pi^2 D^2 N H \sin\phi \cos\phi}{2}$$

- If there is maximum resistance, Q = 0 (Plugged case).

$$\frac{\pi^2 D^2 N H \sin\phi \cos\phi}{2} = \left(\frac{\pi D H^3 \sin^2 \phi P}{12 \eta l} \right)$$

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

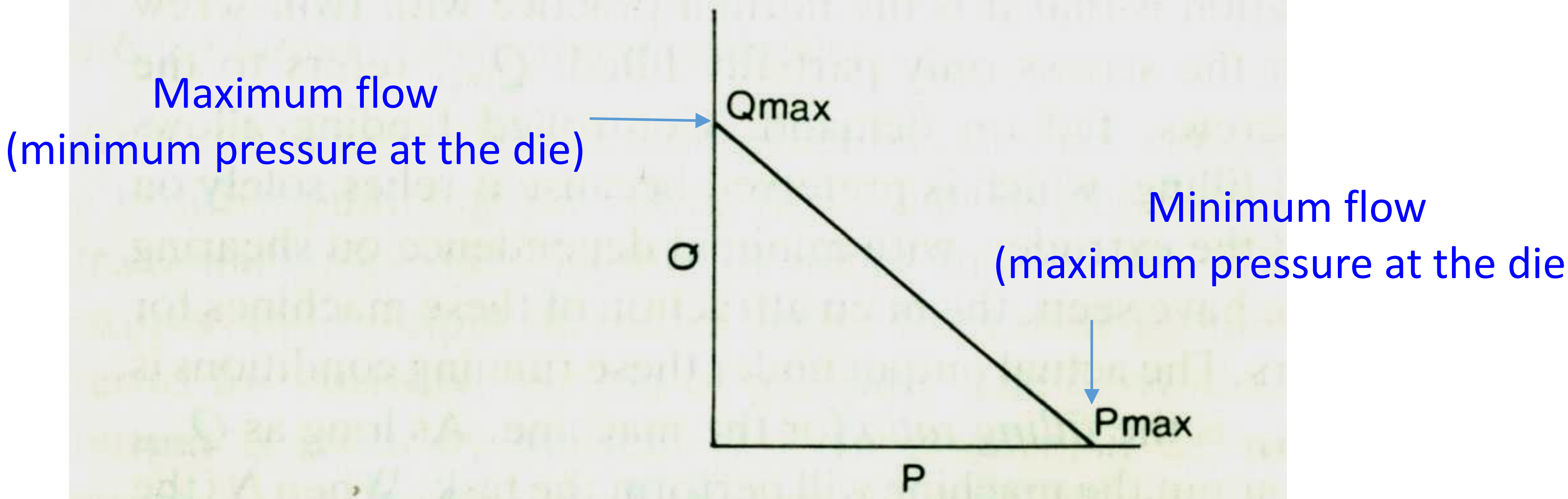


Fig. 4.19 The extruder or screw characteristic.

- A die at the extruder outlet requires head pressure to function; the pressure is needed simply to force the melt through the die.
- The maximum output will result from minimum pressure.

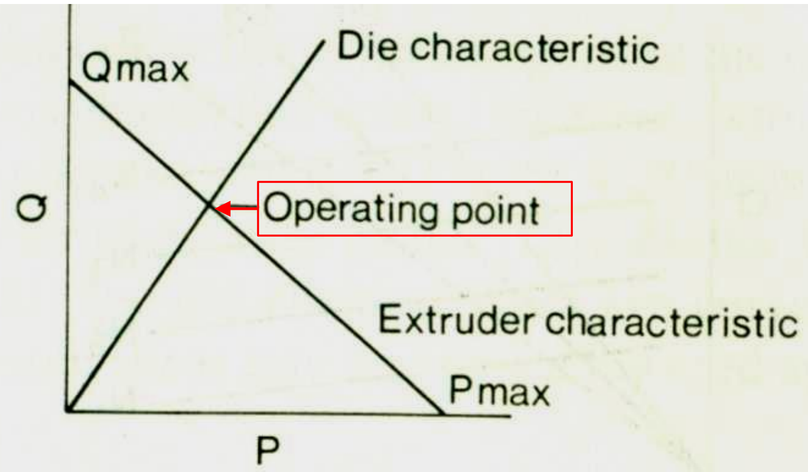


Fig. 4.20 Interaction of screw and die characteristics.

$$Q = KP$$ Flow rate depends on die shape

K is the shape-dependent factor. For cylindrical capillary dies,

$$K = \frac{\pi R^4}{8\eta L}$$

- The output equation for the extruder is

$$Q = \alpha N - \left(\frac{\beta P}{\eta} \right)$$

More flows at the same *P*

Less flows at the same *P*

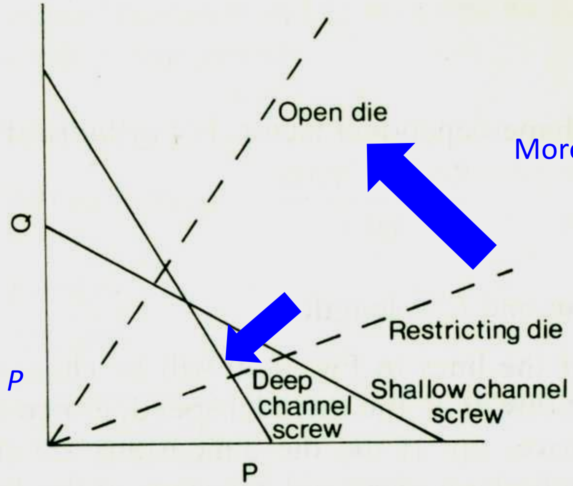


Fig. 4.22 Different matches of screw and die characteristics.

P and Q vary depending on die shapes

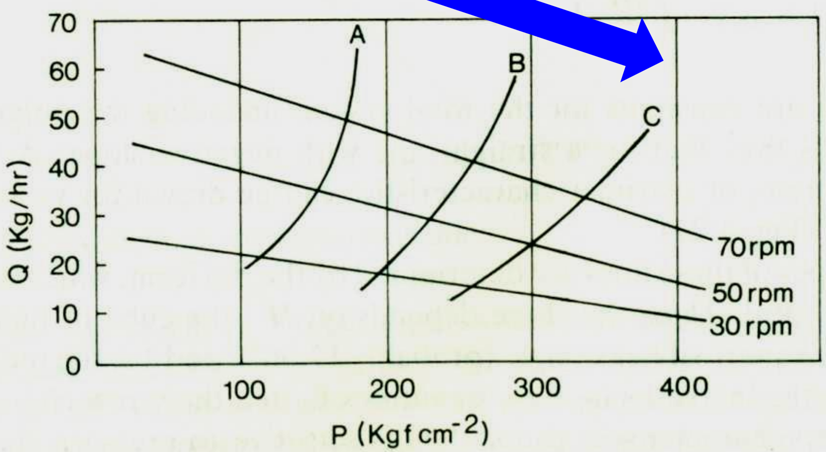


Fig. 4.23 Output characteristics for a 60 mm extruder (60 mm extruder, short compression screw, polyethylene, MFI 0.5, three different die characteristics).

The extrusion die

- Basic flow patterns

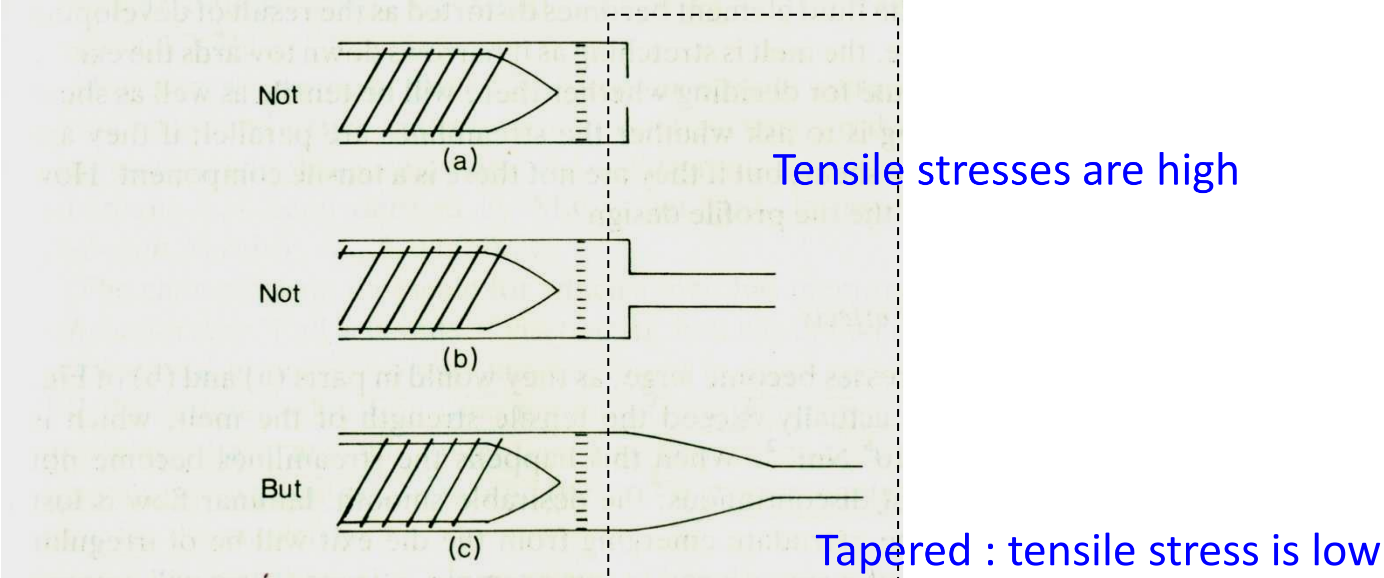


Fig. 4.24 Conjectural patterns for a rod die.

- One needs to maintain for laminar flow in the melt.
- We have to prevent the occurrence of the dead spots where the melt circulates like a backwater and this leads to an extrudate with uneven heat and shear history.

- Die entry effects
  - If the tensile stresses become large (e.g. Fig. 4.24 (a) and (b)), they can actually exceed the tensile strength of the melt (~ 10^6 Pa).
  - As a result, the streamlines become not only chaotic but discontinuous.

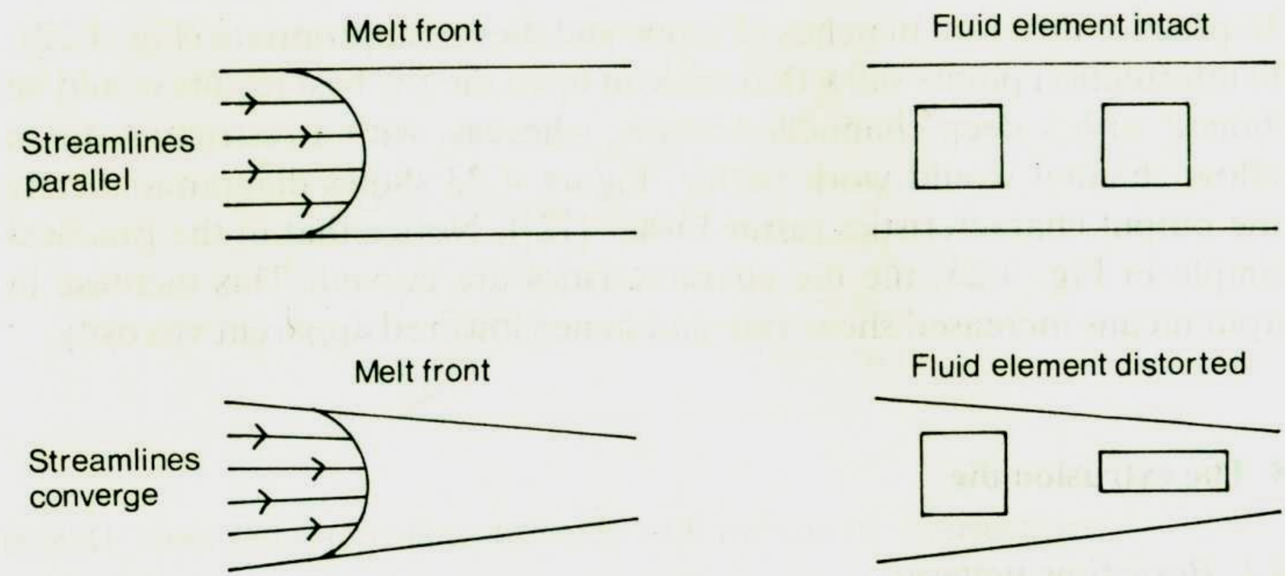
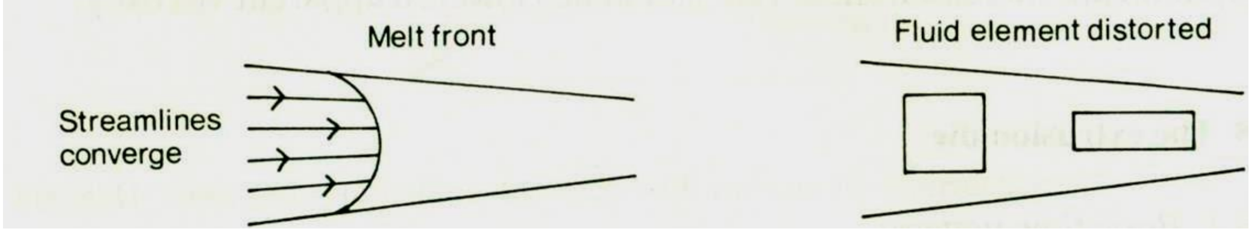
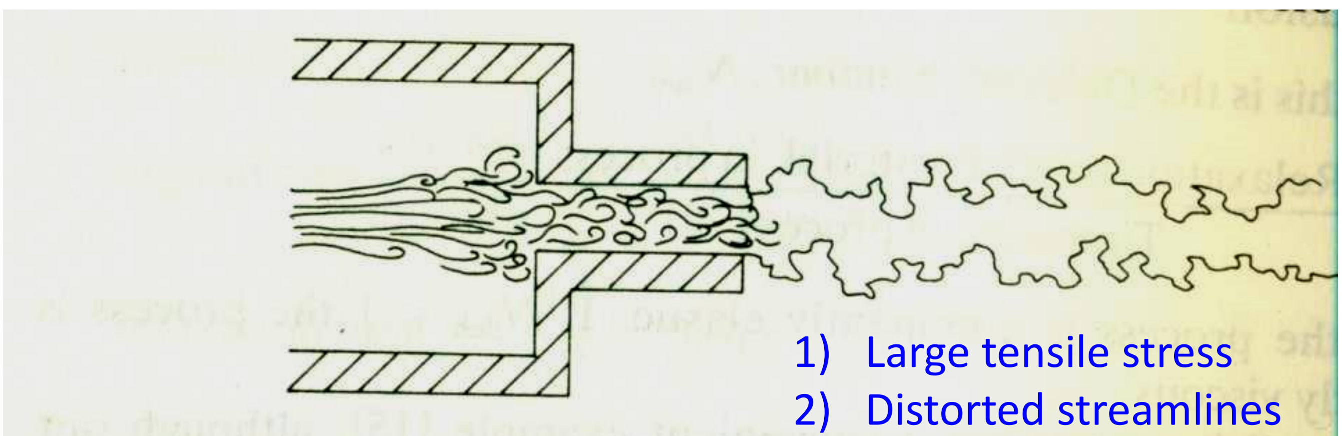


Fig. 4.25 Parallel and converging flows.

- The die entrance is tapered.
    - Eliminate the dead spots in the corners, hence maintaining a steady heat and shear history.
    - Minimize the development of tensile stresses, and hence minimize distortion of the streamlines
    - Extend the process time which helps to eliminate memory of earlier processing, e.g. the screw turning memory.

Tapered channel





1) Large tensile stress
2) Distorted streamlines
→ Turning memory, melt fracture

Fig. 4.26 Melt fracture.

- Viscoelasticity
  - Old testament (Judge V): The song of Deborah and Barak

    "The mountains melted from before the Load"
  - Everything flows if you wait long enough!

- Deborah number, De
  - The ratio of a characteristic relaxation time of a material (τ) to a characteristic time of the process (T)
  - The relaxation time : its viscous and elastic responses to an applied stress.

$$\text{Relaxation time } (\lambda) = \frac{\text{viscosity}}{\text{elastic modulus}} = \frac{Pa \cdot s}{Pa} = s$$

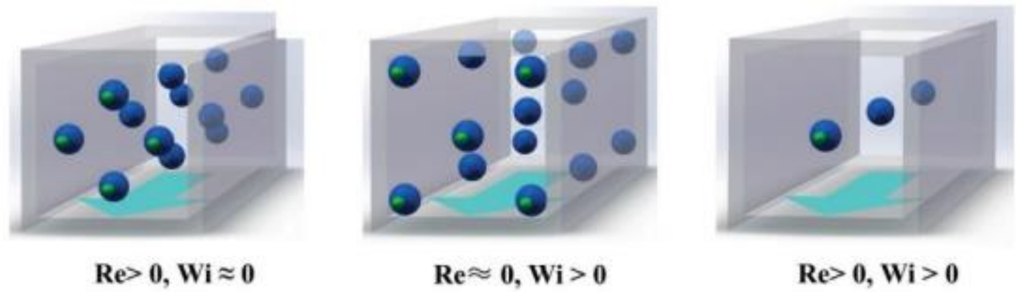
Higher Polymer concentration → higher chain entanglement (resistance to motion) → higher λ → elastic response of the fluid

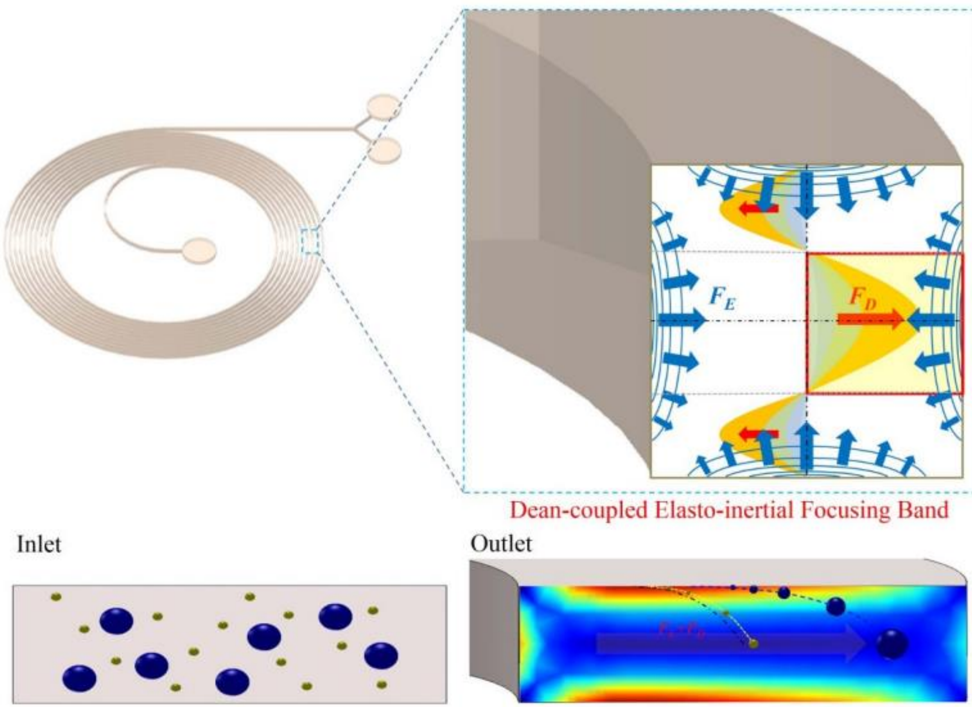
$$\text{De} = \frac{\text{Relaxation time of material, in process}}{\text{Timescale of process}}$$

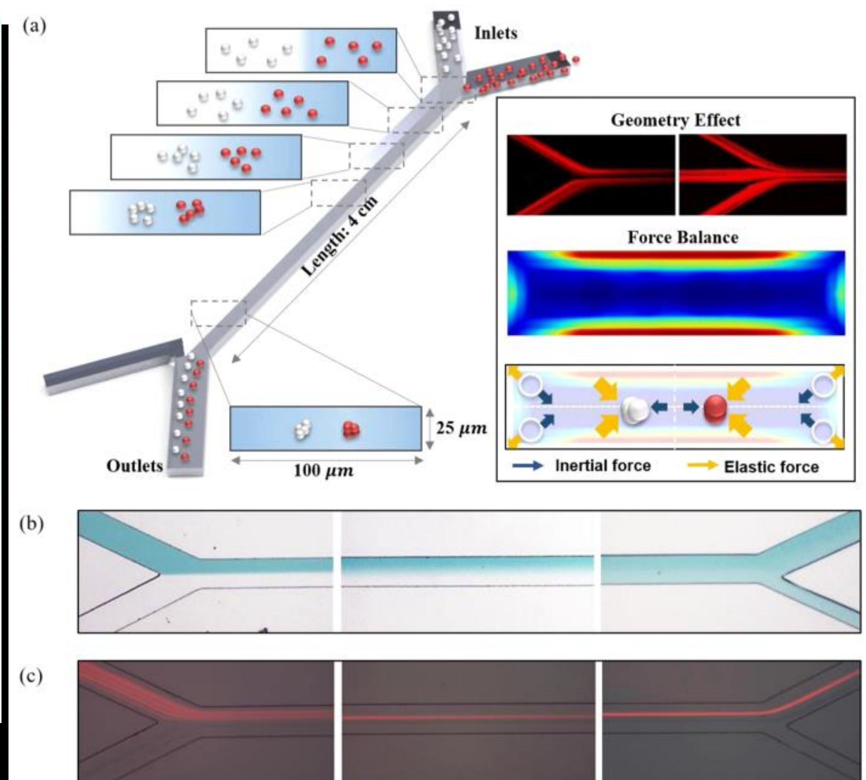
- If De >> 1, the process is dominantly elastic.
- If De ~ 0, the process is dominantly viscous.

- At high *De* (*Wi*) number

: particle focusing induced by normal forces of viscoelastic fluids under high *De* (*Wi*) number







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- Die exit instabilities
  - Shark skin → orange peel → bambooing at a die

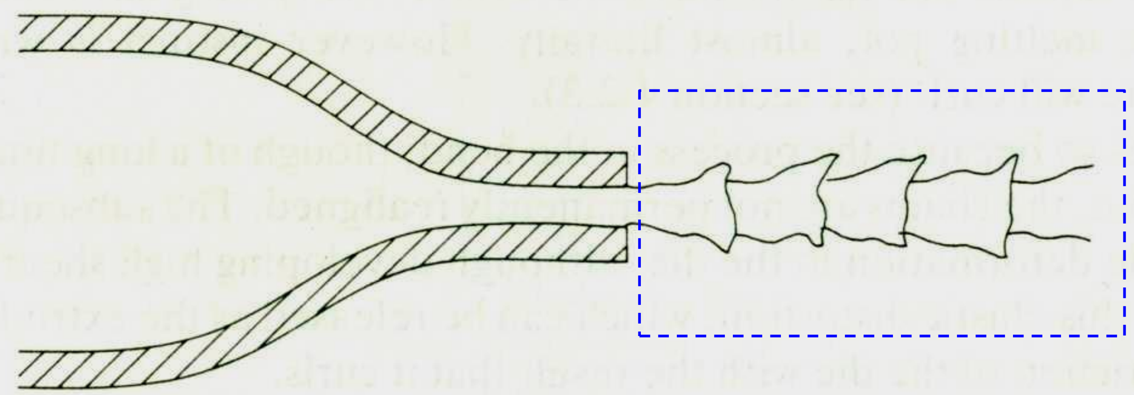

Fig. 4.28 'Bambooing' at a die.

- Structured, highly filled, low elasticity materials most easily show shark skin.
  - When the material leaves the die lip, the material at the wall has to accelerate to the velocity at which the extrudate is leaving the die.
  - This generates tensile stress, and, if the stress exceeds the tensile strength, the surface ruptures causing the visual defect.

- Die swell
  - The die swell results from recovery of the elastic deformation as the extrudate leaves the constraint of the die channel and before it freezes.

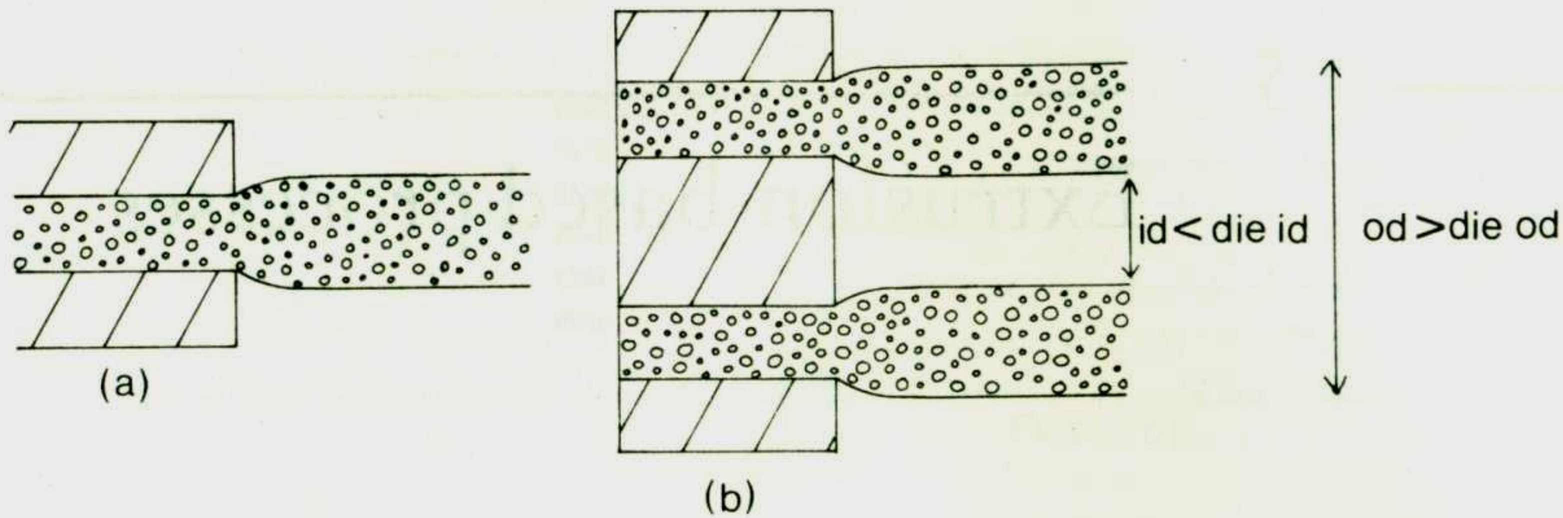

Fig. 4.29 Die swell in (a) rod and (b) pipe.

Question) Does die shrink exist? Why and under what condition?

→ Hint) Find out MWCNT nanocomposites