SINGLE SCREW EXTRUSION ANALYSIS

(book part B - page 5.1)

THE HISTORY OF EXTRUSION
GOES BACK TO
ARCHIMEDES
AND BEFORE
BUT
MODERN DEVELOPMENTS

based on understanding of the physical phenomena are
less than 70 years old.

Modeling of EXTRUSION started in the 1950's at DUPONT

Prominent Names
- McKelvey
- Gore
- Squires

Maillefer (parallel developments in Switzerland, 1950's)

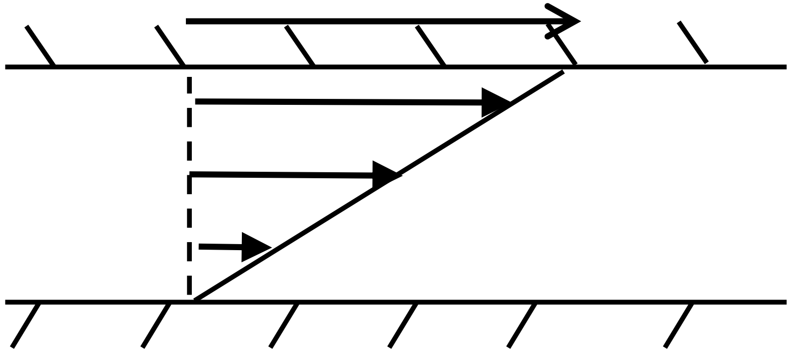
- Maddock (Union Carbide)

- McKelvey's book on P.P. appeared in 1962.
- The book by Z. Tadmor and I. Klein appeared in 1970.

The advent of computers in the 70's, 80's and 90's and beyond led to the sophisticated numerical methods.

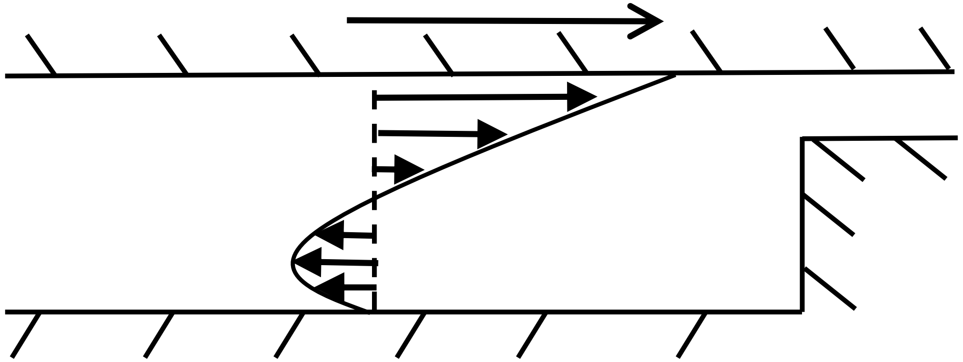
CREATING **A MELT SCREW PUMP**

A **drag flow** pump is simply a device that drags a liquid.



NO pressure
build-up

Closing partially one end we can build up pressure



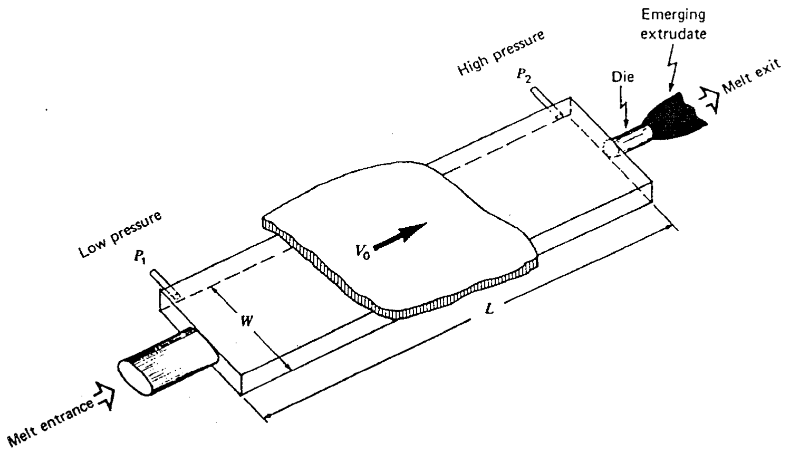
Pressure
build-up

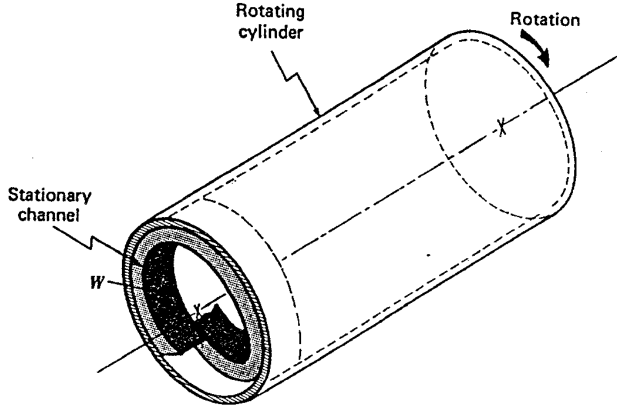
Let's design a device capable of continuously transporting fluid and building up pressure (i.e. a pump)

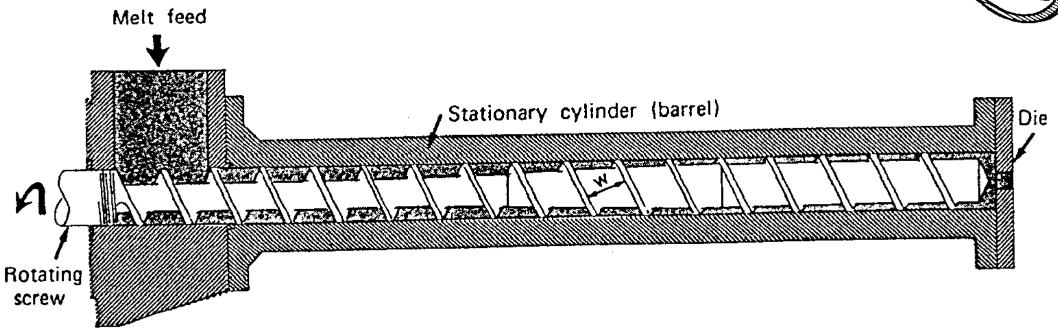
From **Tadmor and Gogos** book: We can also keep the top wall stationary and move the bottom container

or

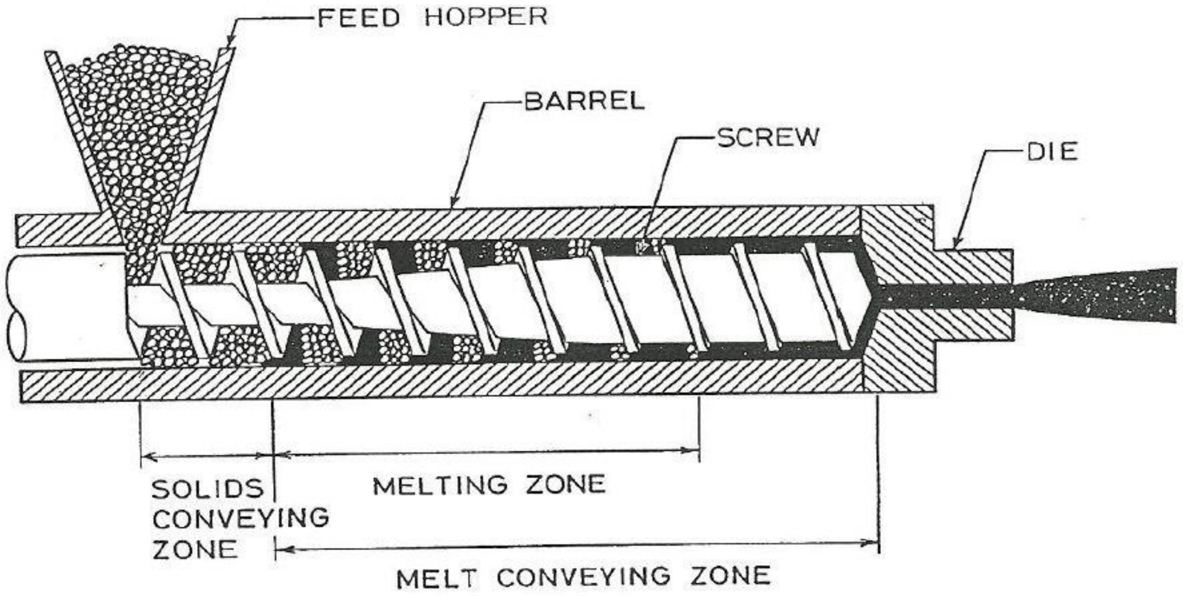
even better let's first twist the container to form a screw and then wrap the wall around it to form a barrel







Conventional Single Screw (also called: plasticating) extruders are composed of three sections:



The polymer pellets or powder are packed into a solid “bed” which is pushed forward, melted and subsequently the melt is pumped through the final flights of the metering section to the die.

SOLID BED TRANSPORT

You must hold the nut in place if you want to move the screw i.e. for the polymer (corresponds to the nut) to move, the **friction coefficient on the barrel must be larger than the friction coefficient on the screw**

- ❖ Barrels → rough surface (some times intentionally grooved) GROOVED FEED EXTRUDERS
- ❖ Screws → smooth (polished) surface

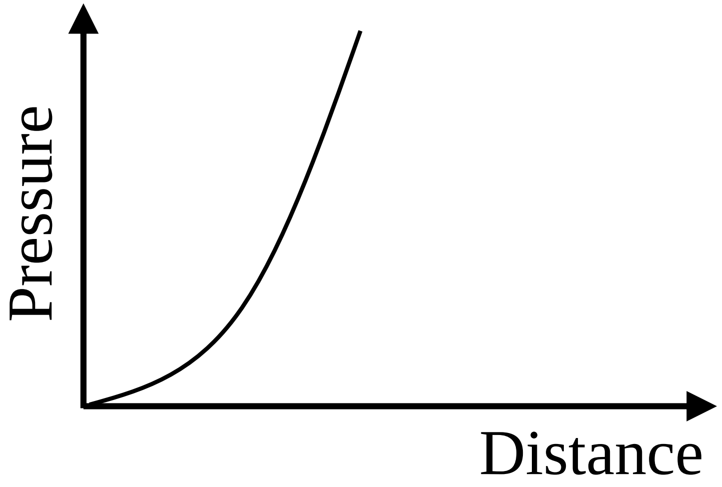
SOLIDS CONVEYING

- Frictional forces and torques are exerted by the “moving” barrel.
- These forward forces are opposed by retarding forces exerted by the root of the screw and flight.
- Pressure is build-up in the direction of flow and the low bulk density solids are compressed into a “sturdy” (hopefully) solid bed, which slides down the channel.
- DARNELL and MOL (1956) developed an isothermal model that relates the mass flow rate to the ratio of outlet to inlet pressure.

Darnell and Moll's model gives pressure rise downstream in the **EXPONENTIAL** form:

$$P = P_o \exp\left\{\left[C_b f_b \cos(\theta + \varphi) - C_s f_s\right]\frac{kZ_b}{A}\right\}$$

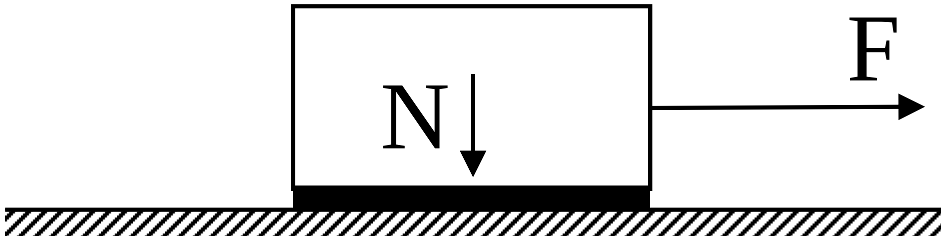
where ***f_b* and *f_s* are the friction coefficients** on barrel and screw C_b and C_s wetted perimeters, φ is the solids conveying angle, Z_b the down channel distance, K, a constant.



The model is very sensitive to values of f_s and f_b.

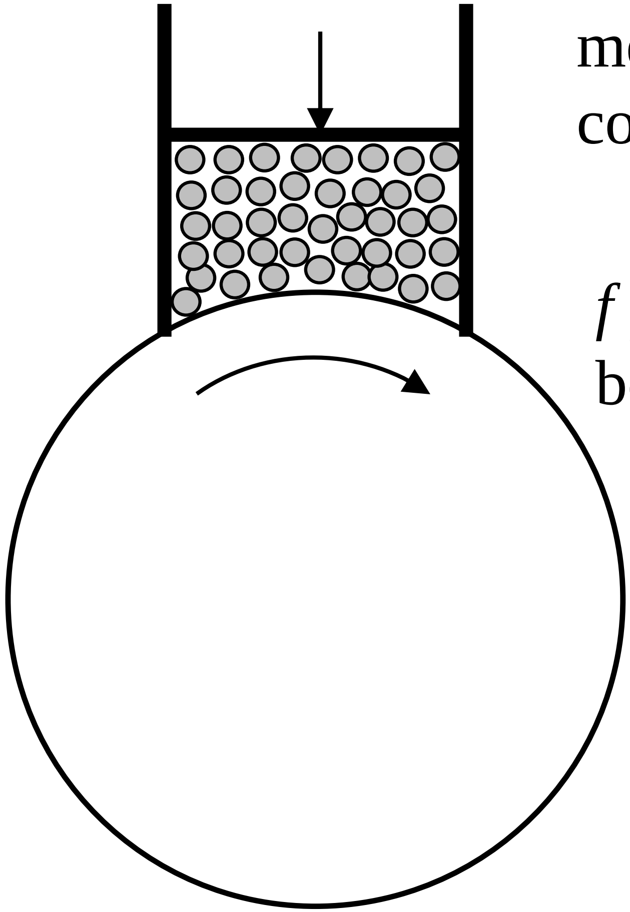
FRICTION COEFFICIENTS

$$F = f\,N$$



Friction coefficient *f*, between the shoe sole and the floor, must be over 0.4 for safe walking

Schematic of device measuring friction coefficient *f*



f pellets/barrel must be over 0.4

f pellets/screw must be no more than 0.25

The accuracy of the model for solids transport depends on the friction coefficients

f_b → solid bed / barrel

$f_b > f_s$

f_s → solid / screw

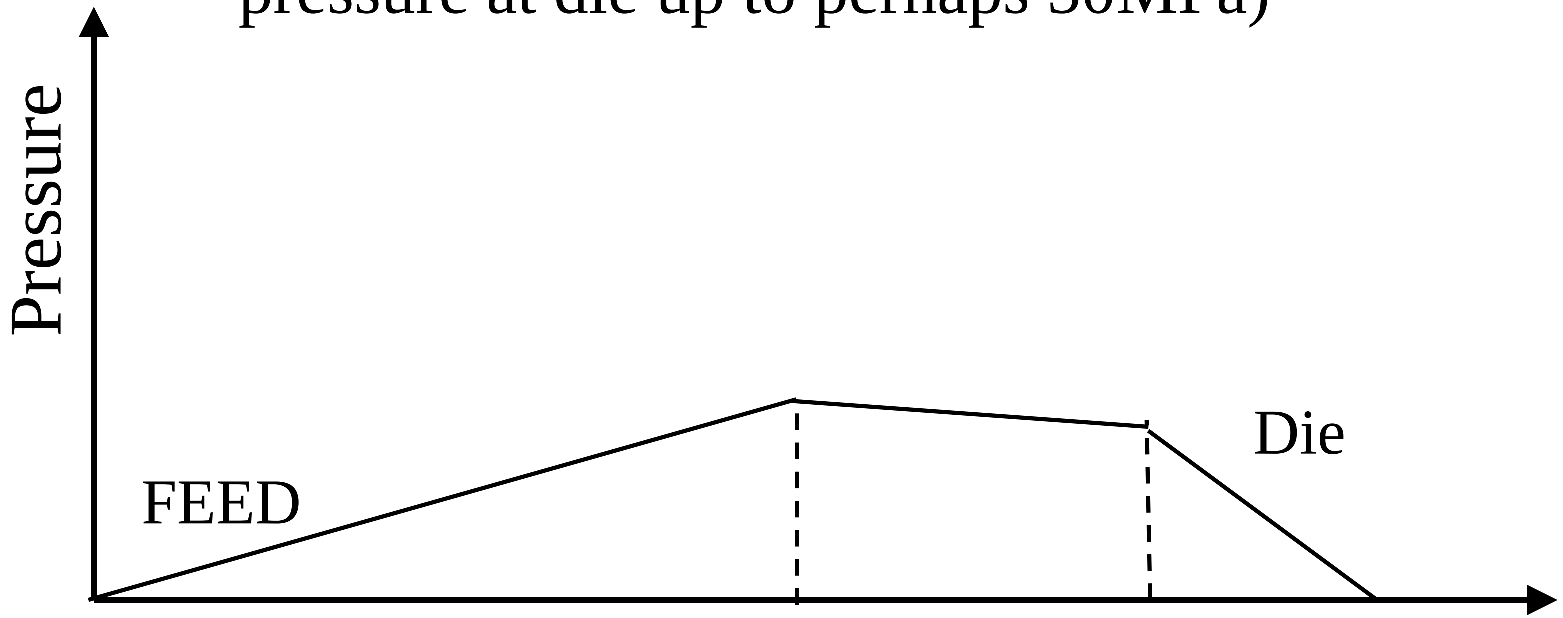
Typical values $f_b \approx 0.4$

$f_s \approx 0.25$

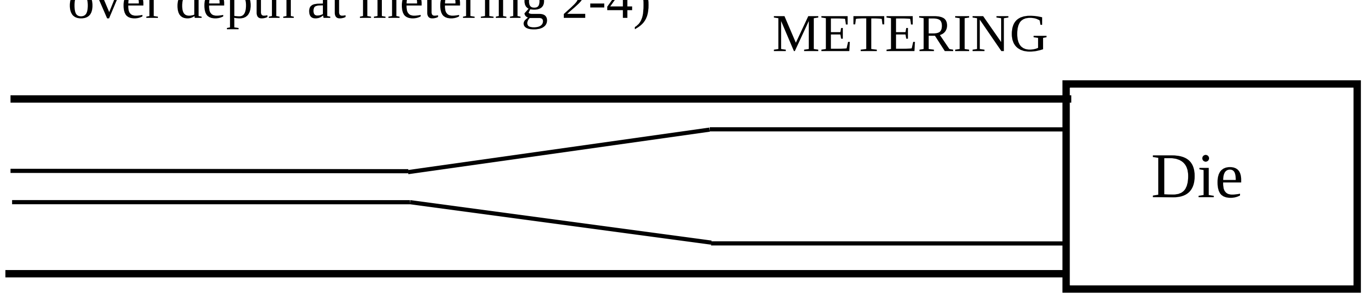
But, f_b and f_s depend on pressure, temperature, surface condition (new, old, worn out), presence of lubricants or additives in the feed, type of feed (i.e. whether pellets, powders, or flakes), shape of pellets and their size, pellet surface (whether smooth or rough).

It is really VERY DIFFICULT to make good and reproducible, and meaningful, measurements.

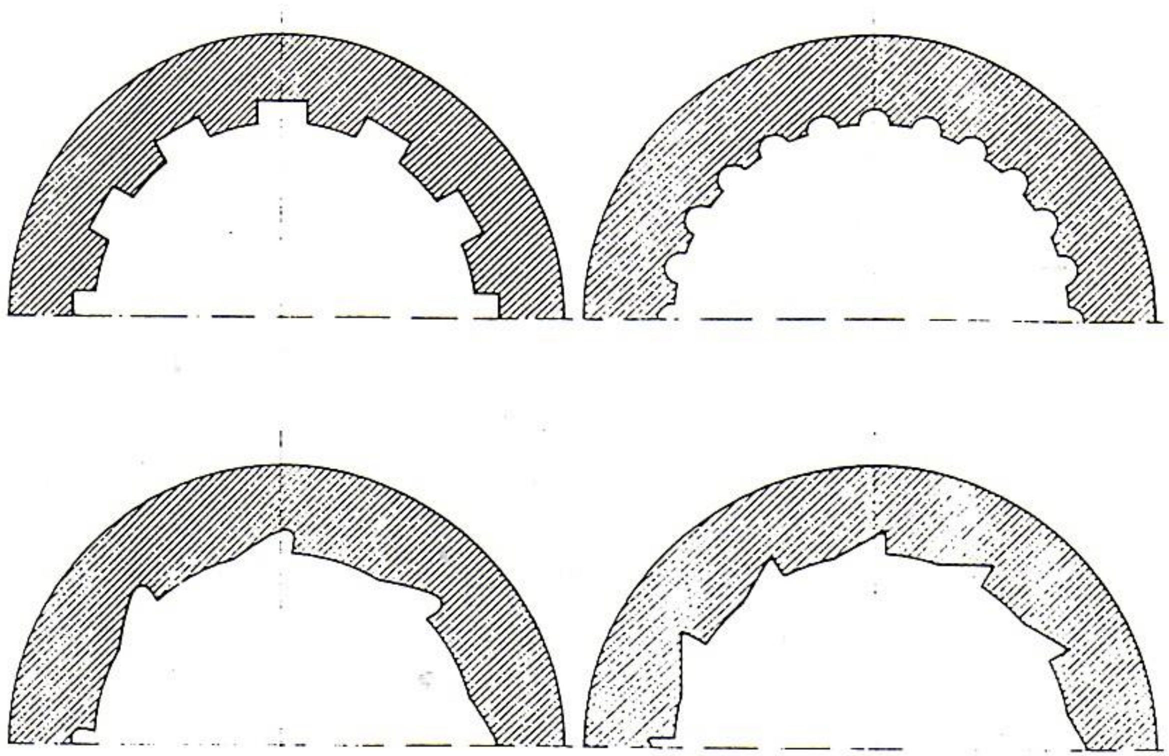
TYPICAL PRESSURE BUILD-UP (**SMOOTH BARREL EXTRUDER**, Maximum pressure at die up to perhaps 50MPa)



COMPRESSION RATIO (depth at feed over depth at metering 2-4)

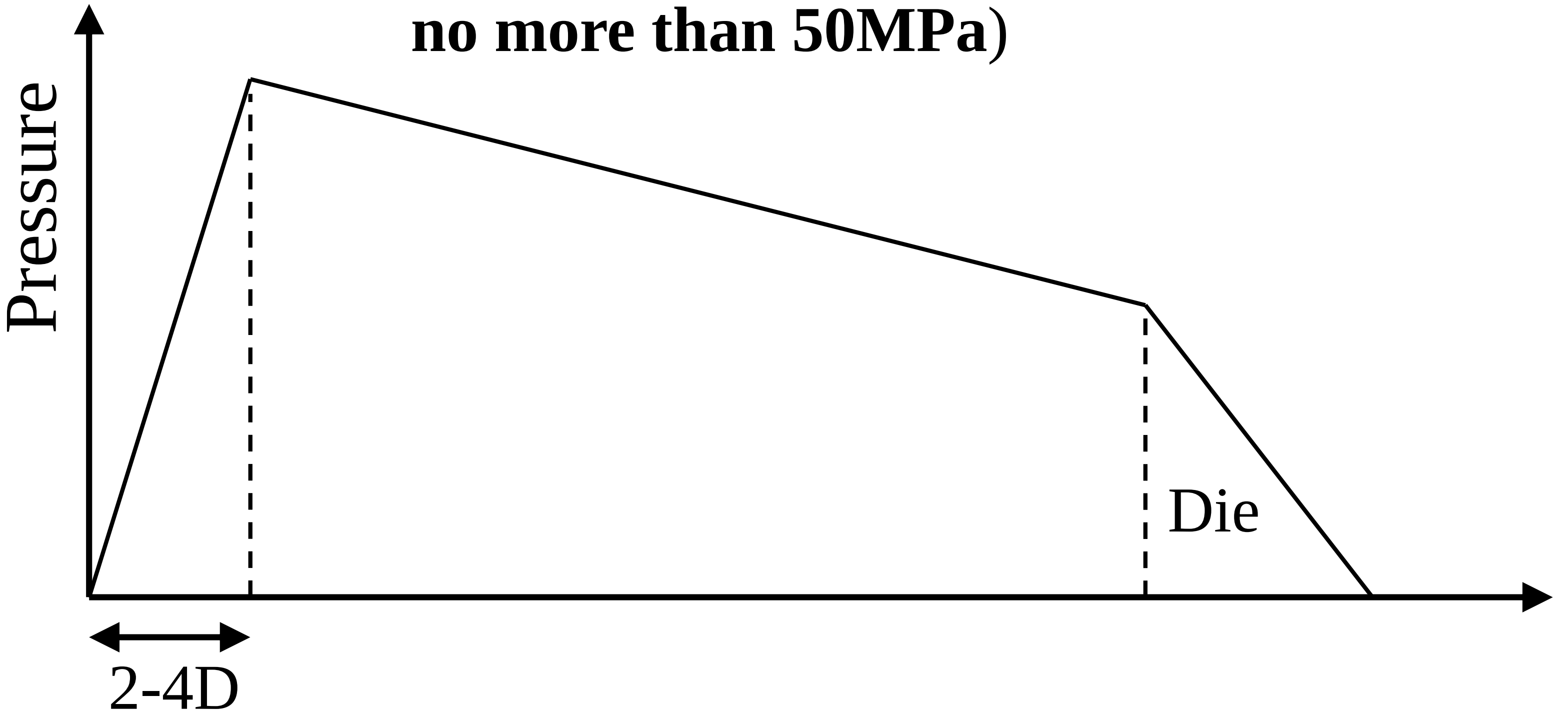


GROOVED FEED

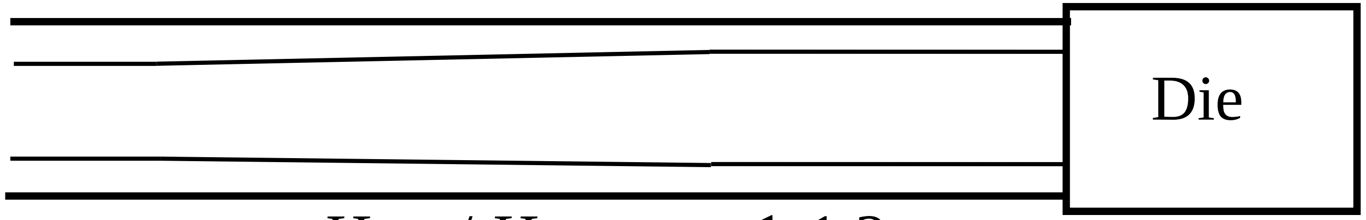


UNDER THE HOPPER USUALLY 2D – 4D LONG

TYPICAL PRESSURE BUILD-UP
(GROOVED FEED EXTRUDER, Maximum pressures over 150 MPa reported. At die maximum no more than 50MPa)



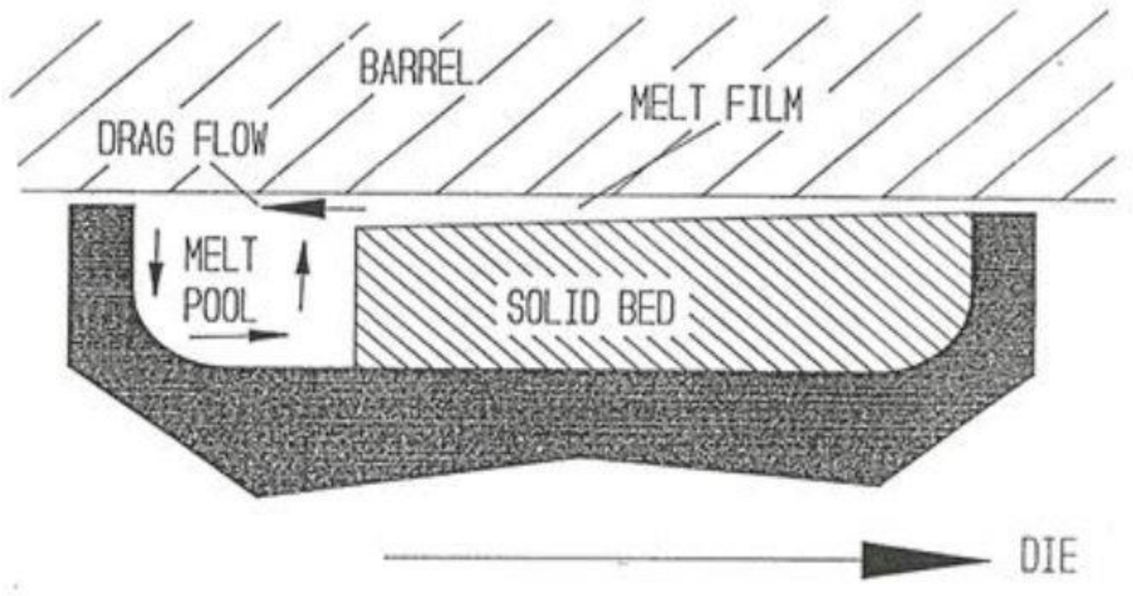
LITTLE COMPRESSION



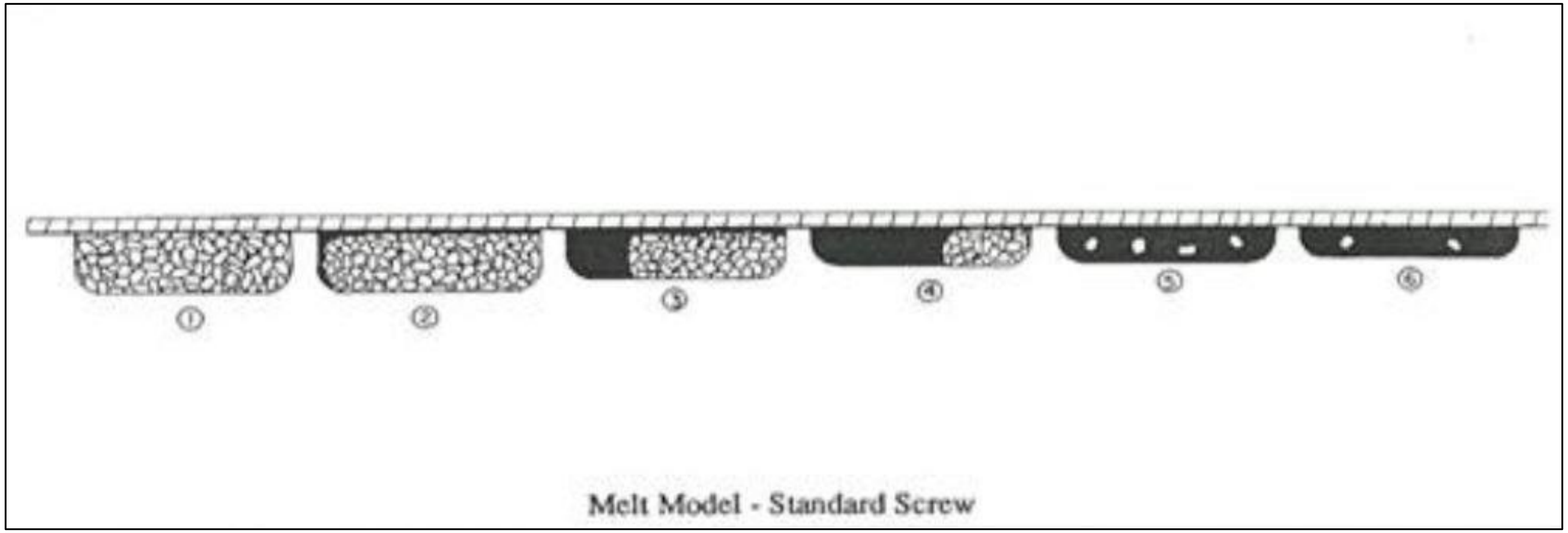
$H_{feed} / H_{metering} \approx 1\text{-}1.2$

MELTING

In the late 50’s, Bruce Maddock did experiments, pulling the screw and examining what happened. The conclusion was that **MELTING** REALLY **OCCURS IN A FILM BETWEEN BARREL AND SOLID BED**. A MELT POOL FORMS IN FRONT OF THE REAR FLIGHT, as shown:



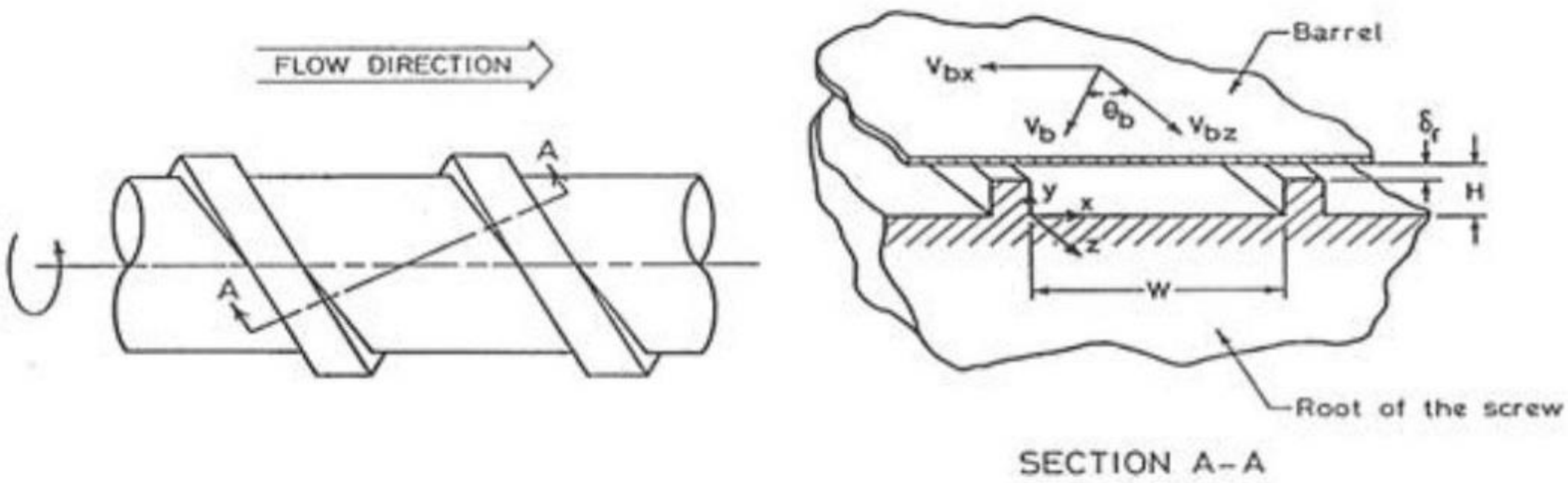
MELTING MODEL SKETCHED ON THE BASIS OF BRUCE MADDOCK'S SCREW PULLING EXPERIMENTS



For more information:
Z. Tadmor and I. Klein, "Engineering Principles of Plasticating Extrusion",
Van Nostrand Reinhold, New York (1970)

MELT PUMPING

The **melt is dragged by the "moving" barrel surface**. Actually, it is the down channel component V_{bz} that drags the melt towards the discharge end.



The cross channel component V_{bx} induces a cross-channel circulatory pattern that results in relatively good mixing.

The flow rate is determined by

$$\boldsymbol{Q_{smooth\ barrel} = Q_{drag} - Q_{pressure(head)} - Q_{leakage(over\ flights)}}$$

If grooved barrel, the pressure flow caused by the "overbite" must be added.

For the Newtonian, isothermal case it is easy to write the appropriate expressions (see Appendix)

$Q_{grooved} \approx 1.5 Q_{smooth}$ for same diameter
up to $2.0 Q_{smooth}$

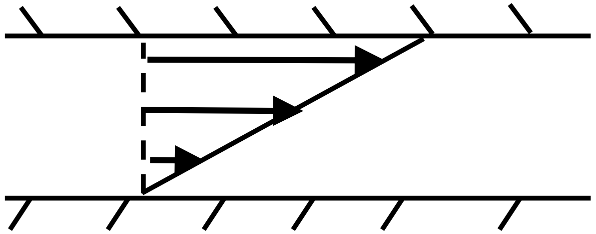
Although, we talk about pressure backflow, there is under no condition backward flow along the screw axis.

- The velocity profiles are shown on next figure
- The path of fluid particles in the screw channel is very interesting

SINGLE SCREW EXTRUDER THROUGHPUT

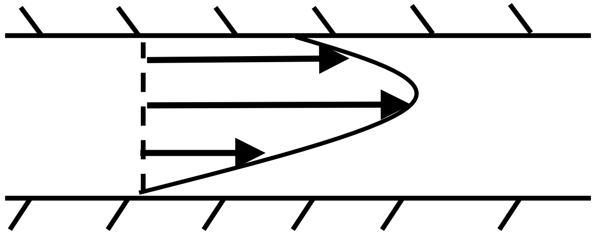
Let's get an estimate of throughput.

No matter what happens in the solids-melting or metering zones the throughput is really determined by the metering zone.
We have either:



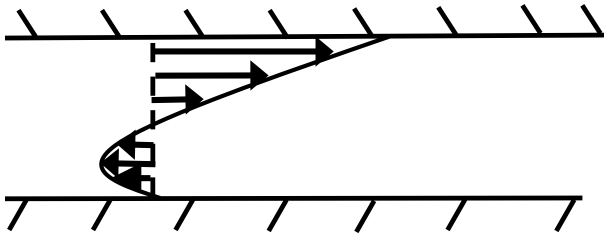
Ideal drag flow (e.g. smooth barrel extruders)

Or



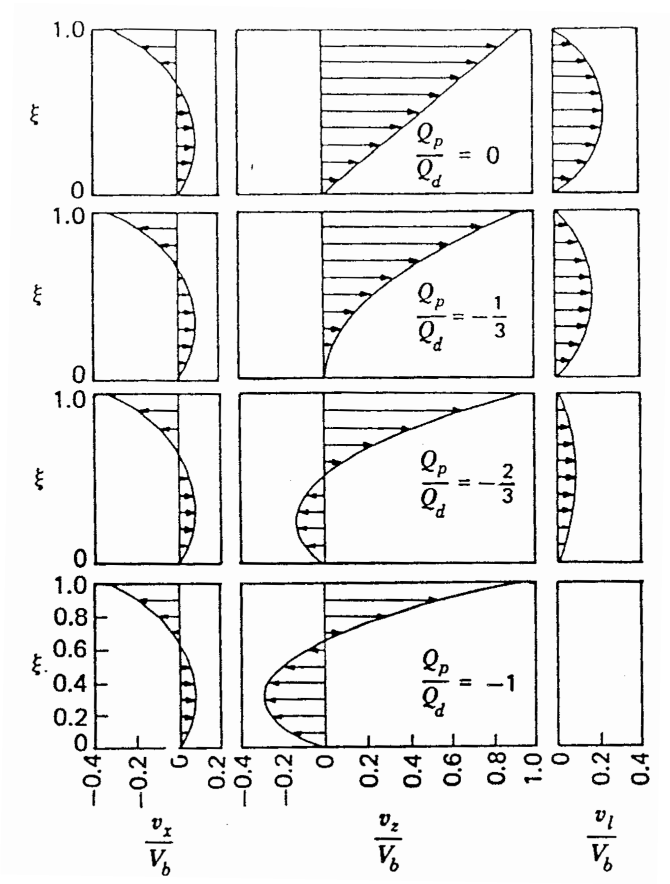
Drag flow plus pressure flow (positive) if the extruder tends to "overbite" in thsolids zone (e.g. **grooved barrel extruders**)

Or



Drag flow minus (negative) pressure flow if the pressure in the die (head pressure) is too high

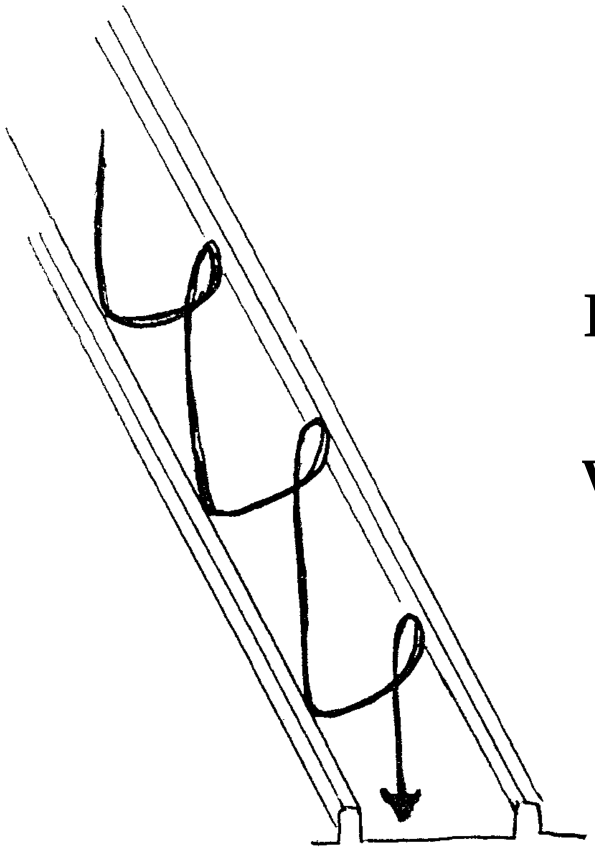
VELOCITY PROFILES



cross channel

down channel

axial



Spiraling flow down the channel.

It is like “helix” within a helix

This means that there is under no condition backward flow along the screw axis

Industrial experience shows that for good functioning extruders the **throughput should not be less that 25% of drag flow** throughput (watch out for the units)

$$Q_D = \frac{1}{2}\pi^2 D^2 HN \sin\theta \cos\theta$$

Barrel (D)

Channel depth in the metering section (H)

RPM (N)

usually 17.66° (θ)

or corrected to account for screw flight width:

$$Q_D = \frac{1}{2}\pi^2 D^2 HN \sin\theta \cos\theta \left(1 - e/T\right)$$

screw flight width (e)

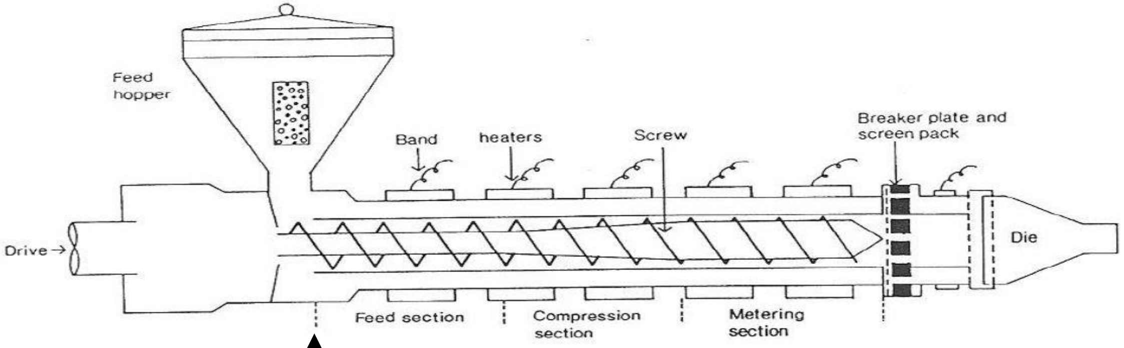
screw pitch (T)

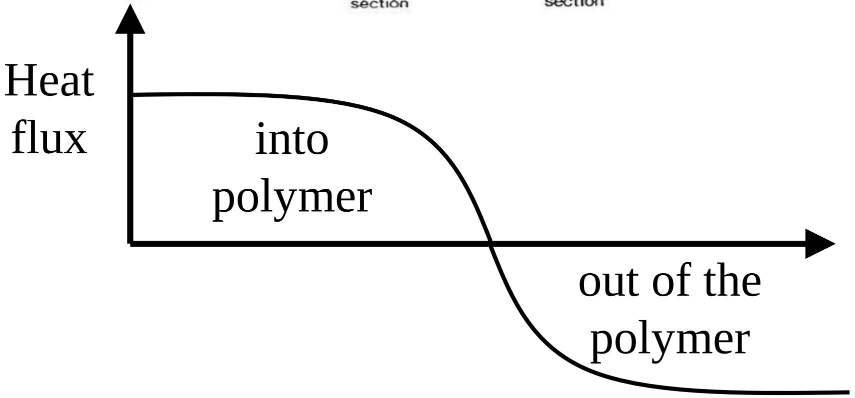
You get (**at least 50% more**) with **GROOVED FEED** extruders

$$Q_{grooved} \approx 1.5 Q_{smooth}$$

POWER REQUIREMENTS

- In the extruder polymer pellets usually coming in at room temp. (i.e. 20^{o} C) are melted and subsequently pumped at the extrusion temperature through the die (i.e. 200^{o} C, lower or higher, depending on polymer)
- **Most of the energy comes from the turning of the screw.** Of course, some energy is supplied by the heating bands around the barrel.
- In well turning extruders usually net input of energy occurs in the first section (near the hopper) and net output in the second section (near the die) i.e. the heat generated by viscous dissipation is really heating the barrel.





The power required by the turning screw is needed to:

1. **Raise the temperature from Room Temp. to Extrusion Temp.**
   (mass × specific heat × ΔT)
2. **Melt the polymer (Heat of fusion) (mass × ΔH_f)**
3. **Pump the molten polymer (ΔP × volume flow rate)**

- ΔT: Temperature difference (OUT - IN)
- ΔH_f : **Heat of fusion (ice: 333,000 J/kg, HDPE: 250,000 J/kg, PS (amorphous): zero)**
- ΔP: pressure drop at the die (max of 50 MPa (7250 psi))

$$P_o = \rho Q C_p\left(-T_{in} + T_{out}\right) + \rho Q H_f + Q\Delta P$$

ρQ : throughput (kg/h)

C_p : heat capacity (avg.) ~ 2000 – 3000 J/kg^{o}C

T_{in} : usually room temp. (20^{o}C)

T_{out} : usually 200 – 300^{o}C

ρ: (avg.) ~ 700 – 1200 kg/m^3

H_f : heat of fusion

For LDPE ~ 130,000 J/kg (cryst.)

For PS ~ theoretically zero (amorphous) i.e. no heat needed to melt it at the "melting point"

$\Delta P \rightarrow$ head pressure usually 10 MPa to 50 MPa

$Q \rightarrow$ volume flow rate $\left(\rho Q / \rho = \dot{m} / \rho\right)$

Let's calculate the relative contributions for 124.22 kg/h of LDPE and pressure rise of 30 MPa:

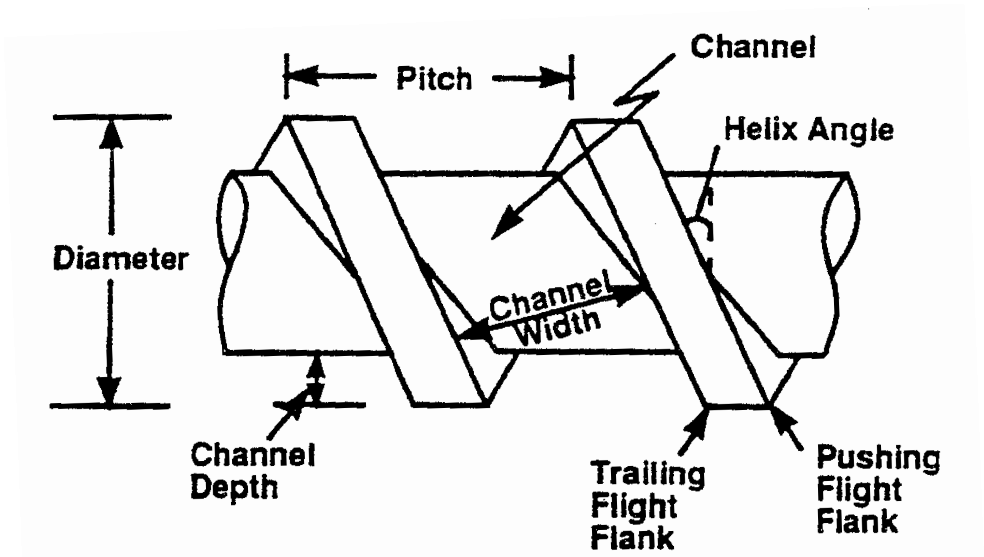
P_o =124.22×2500×(200-20)
+124.22×130,000
+30×10^6×124.22/760
=**55,889 kJ/h (most important TO RAISE TEMPERATURE**)
+**16,148 kJ/h** (**somewhat important TO MELT)**
+**4,903 kJ/h** (**insignificant TO PUMP)**
(this means that the extruder is an inefficient pump)
=76,950 kJ/h (then multiply by 1/3600)
$=21.37\ \text{kJ/s}=21.37\ \text{kW} \times \left(\frac{1}{0.746}\right) \approx 28.65\ \text{hp}$

So we can size the HP (horsepower) of a motor. But we must take also into account its efficiency:
Assume 85%, then: Motor power = $\frac{1}{0.85} 21.73 = 25.14\ kW = 33.7\ hp$

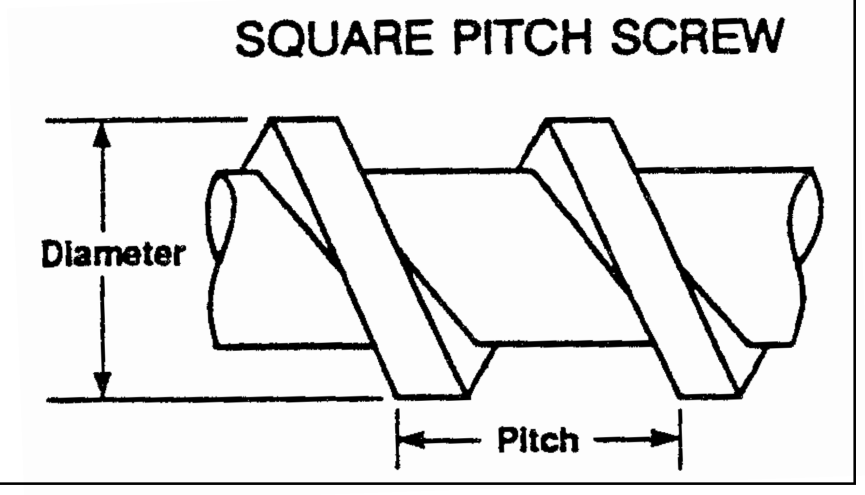
Very frequently the specific power requirement is a very useful quantity:

$$e = \frac{P_o}{\dot{m}} = \frac{25.14\ kW}{124.22\ kg/h} \approx 0.2 \frac{kWh}{kg}$$

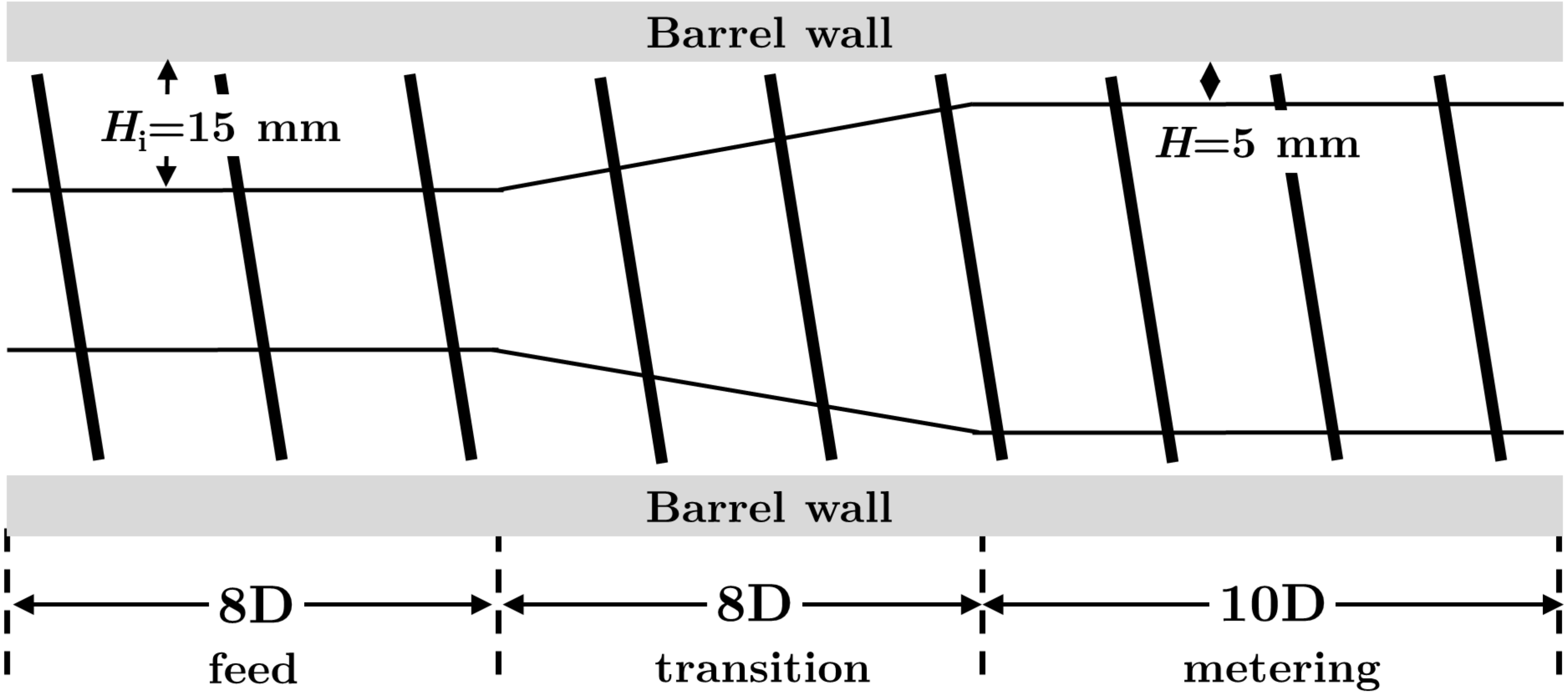
SCREW TERMINOLOGY



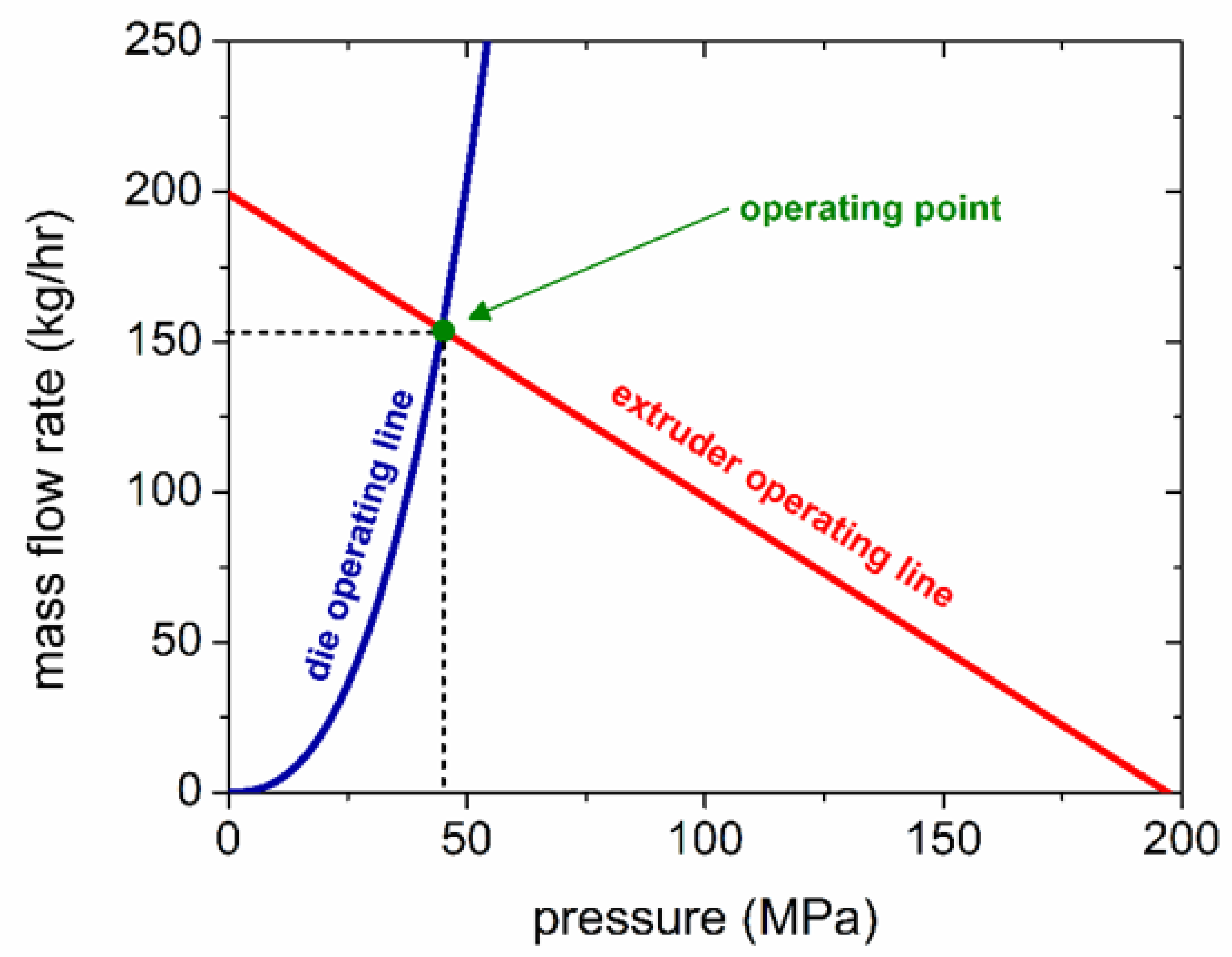
If pitch is equal to the screw diameter, it is called square pitch and the helix angle is θ=17.66°.



Typical 100mm extrusion screw profile



Operating Point



The general purpose extrusion screw

- Screw Length: L=24D~36D (18D~24D in Injection Molding)
- Feed : 4D~8D (Injection Molding: feed 50%, Trans. 25%, Meter. 25%)
- Metering section: 6D~10D
- Helix Angle θ = 17.66 ($L=\pi D\tan\theta$, flight pitch $L=D$ "square pitched", LEAD is same as PITCH in single-flight screws)
- Flight width 0.1D
- Channel depth in the feed section (a good first guess)

  $H_f=0.11\times(D+25)$ mm ($H_f=0.08\ (D+25)$ for Injection Molding screws)
- Compression Ratio (H_f/H_m)=2~4 (recommendations for different materials next slide)

Compression ratios (H_f/H_m)

- **HDPE (3.0-3.5), LDPE (3.5-4.0), PP (3.0-4.0)**
- **U-PVC (1.75-2.75), P-PVC (2.5-3.5)**
- **PMMA (1.8-2.8), PET (2.3-3.2)**
- **PC (2.25), PA66(3.0-4.0)**
- **TPE (3.5)**

HELIX ANGLE (usually not altered)

Very frequently squared-pitched screw
(lead is equal to diameter)

$\theta = 17.66°$

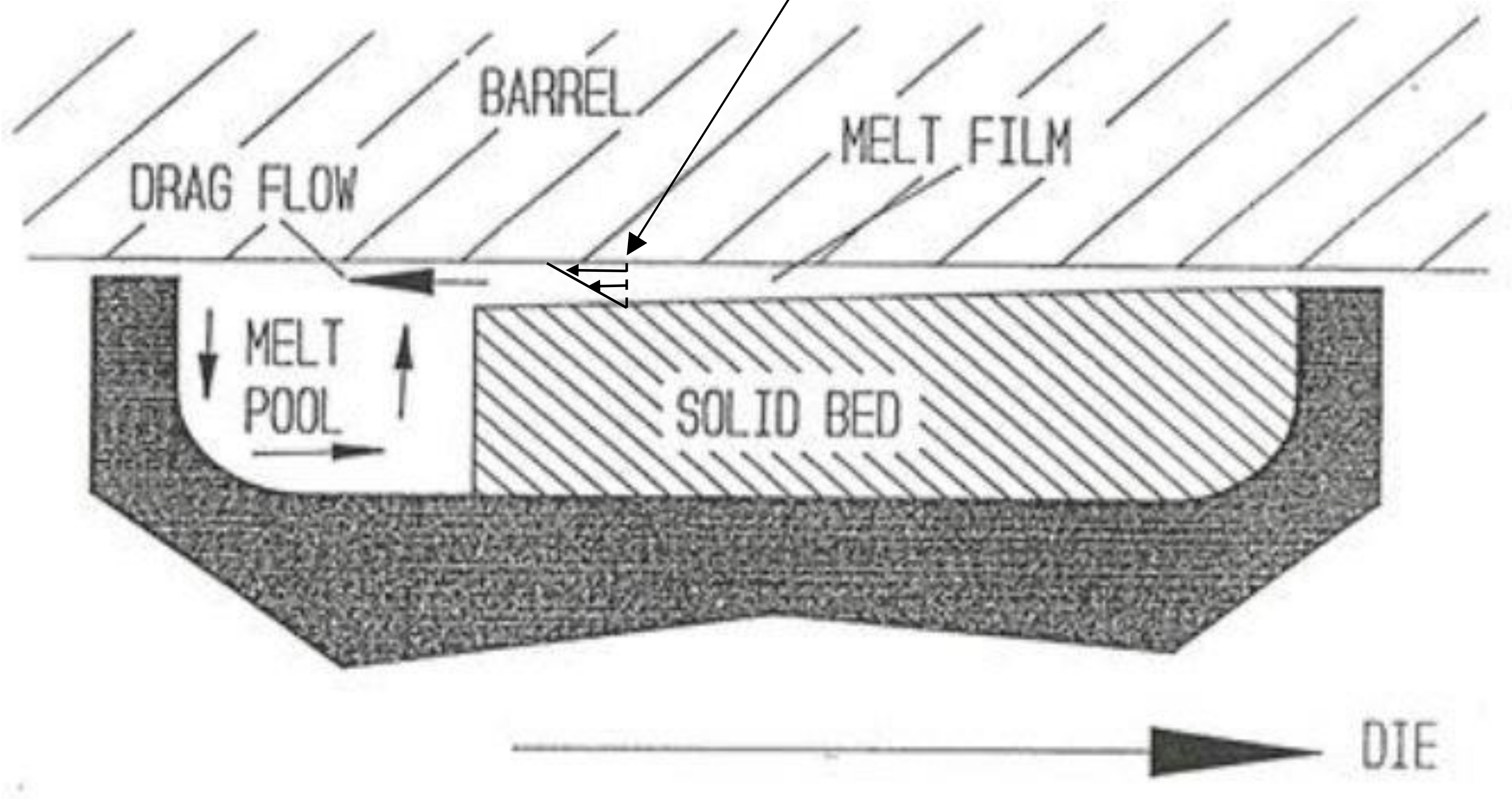
Greater angle means
LESS SHEAR and HIGHER OUTPUT

Smaller angle means
MORE SHEAR and LESS OUTPUT

BARRIER SCREWS are used increasingly not only in extrusion but also in injection molding

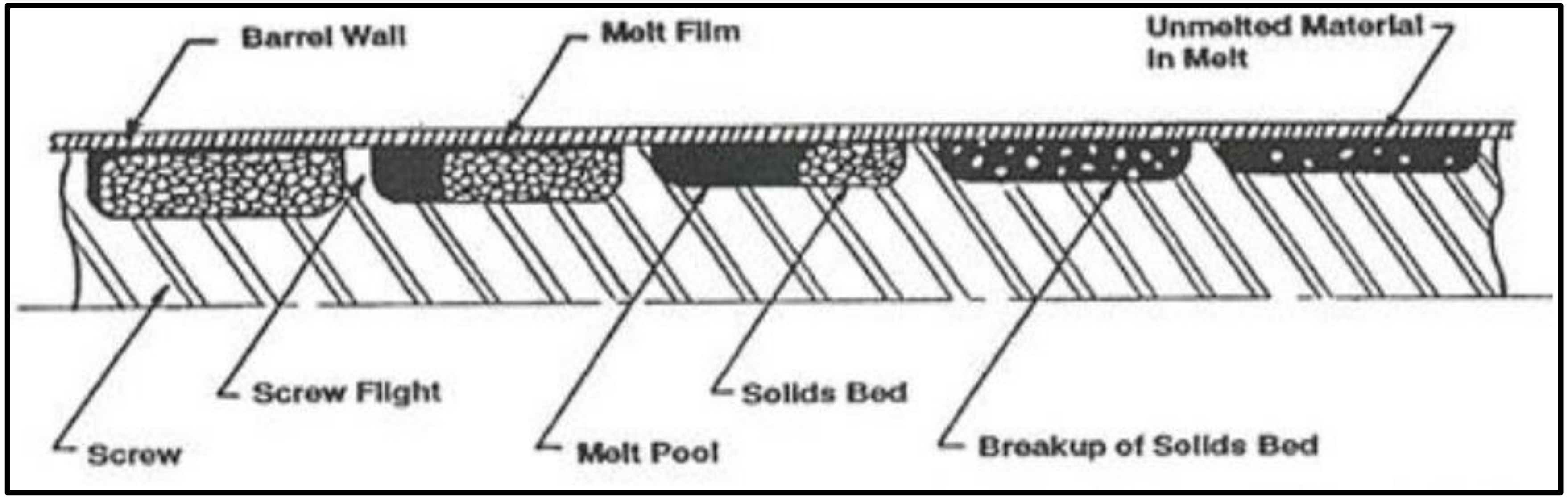
For improved melting

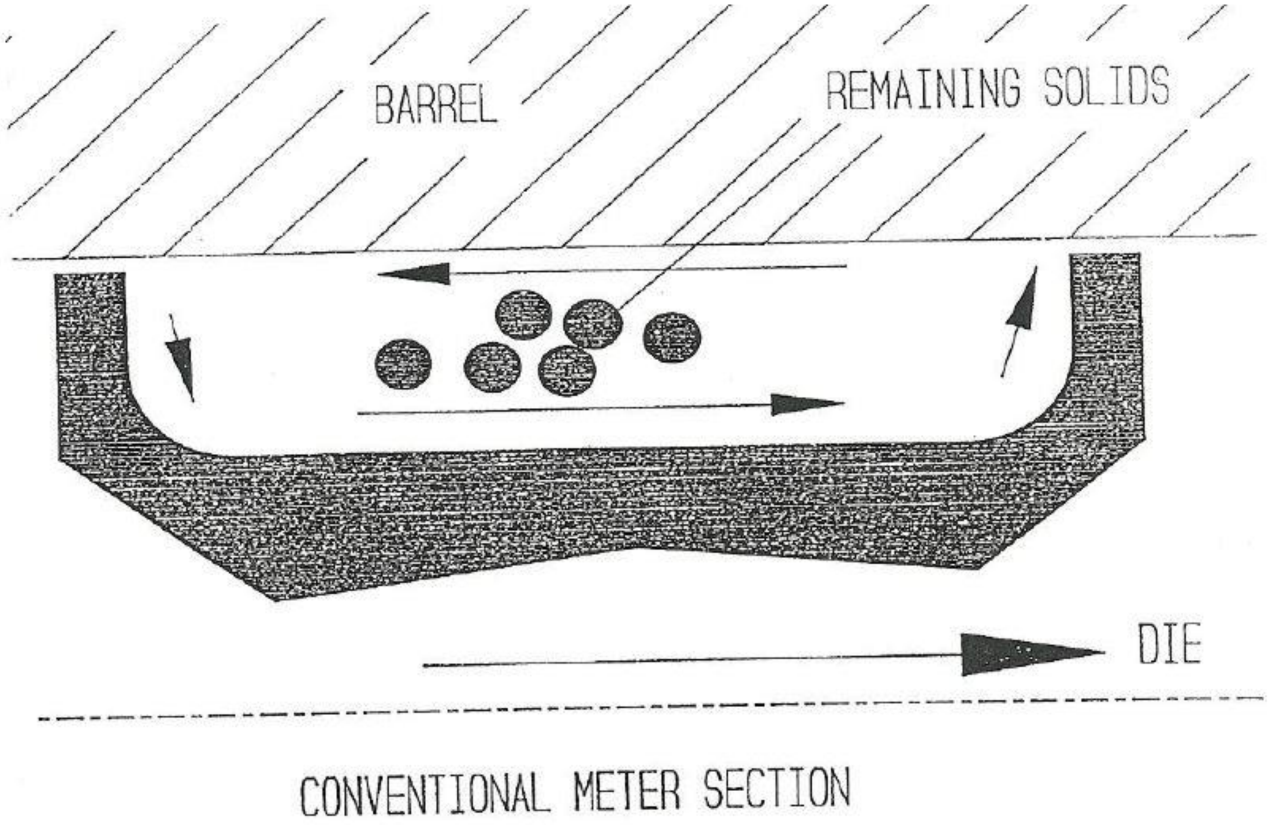
Shear is the primary source of melting



conventional screw melting

In all screws at least the first 70% or so of melting is due to the shear stress in the melt film between the barrel and the solid bed surface.

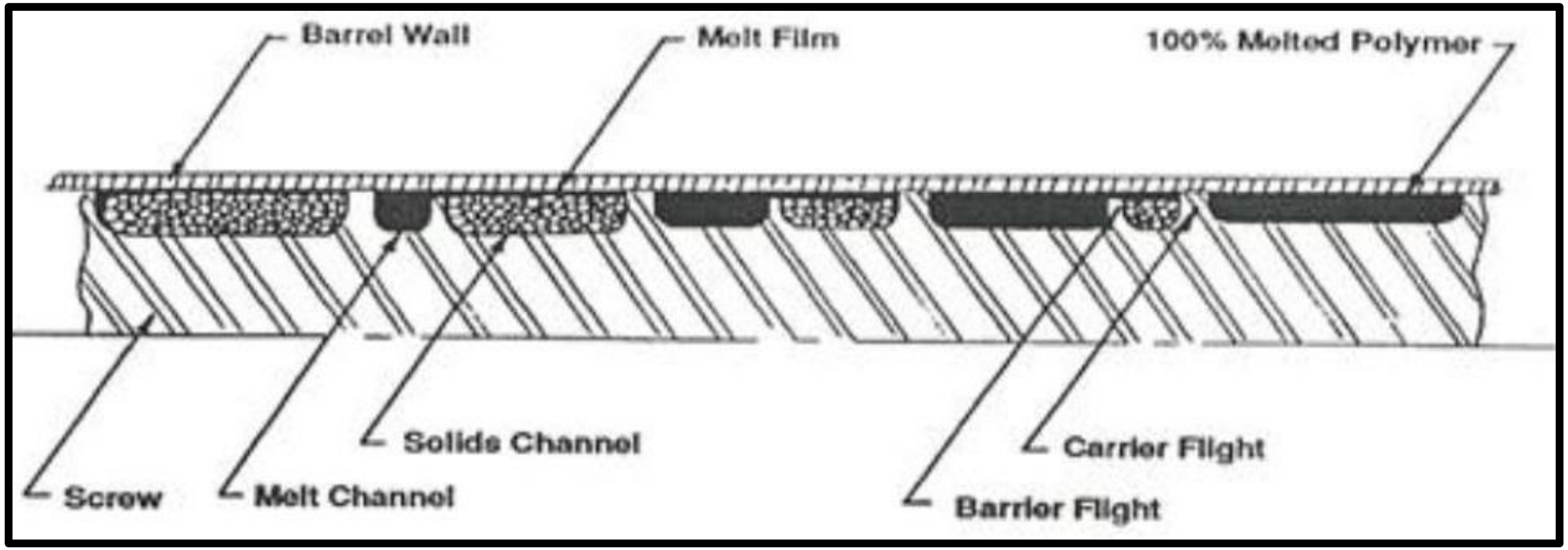




Conventional metering section

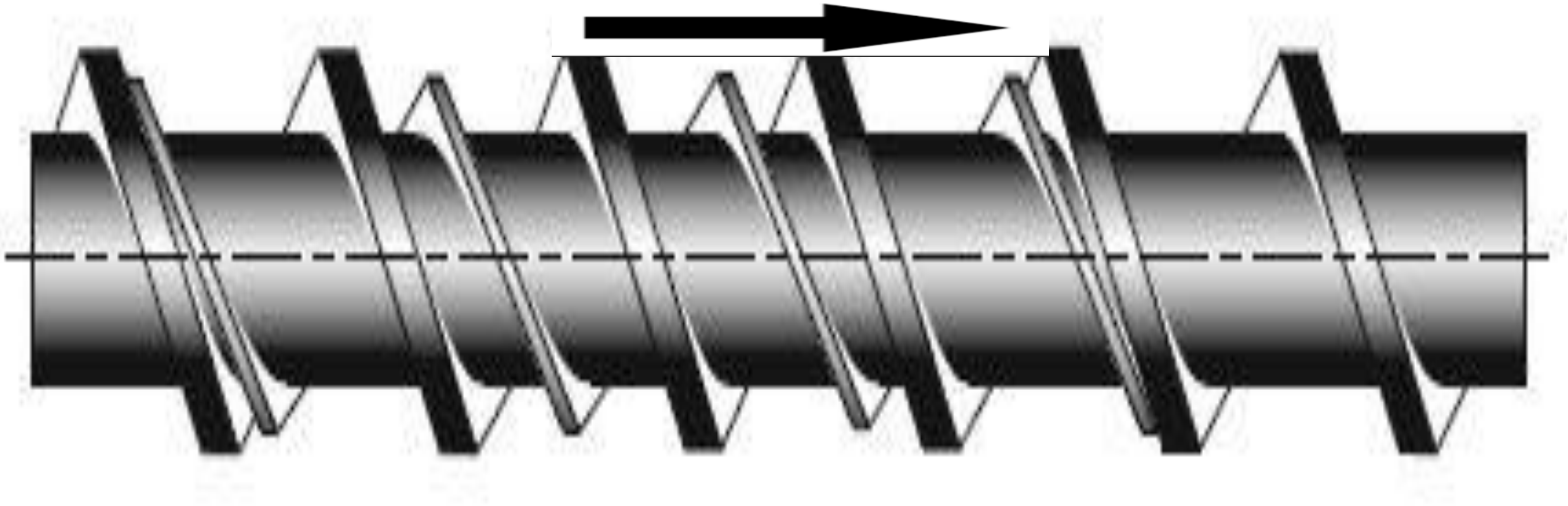
The solid bed is fairly <u>easily</u> subject to breakup (especially at the end of the compression section…) and the remaining solids will receive very little shear….unmelt.

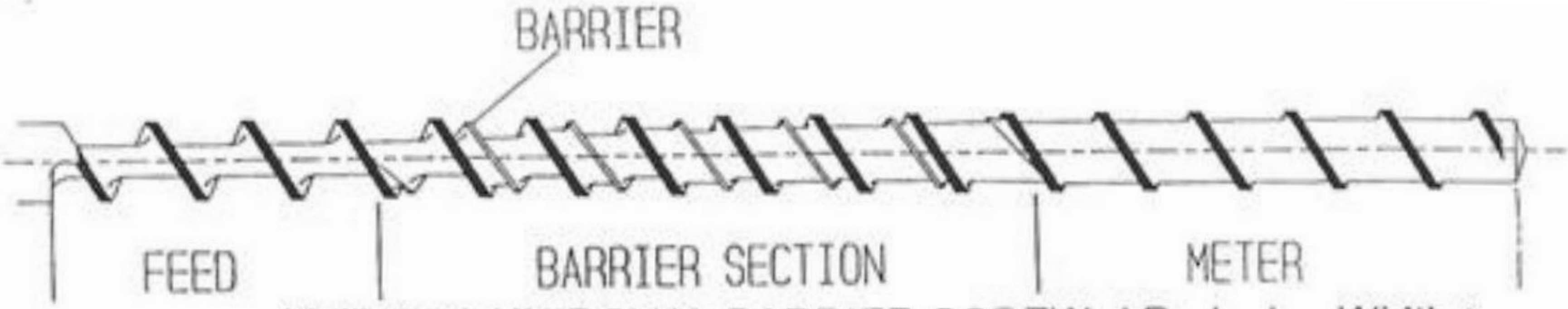
BARRIER SCREW PRINCIPLE



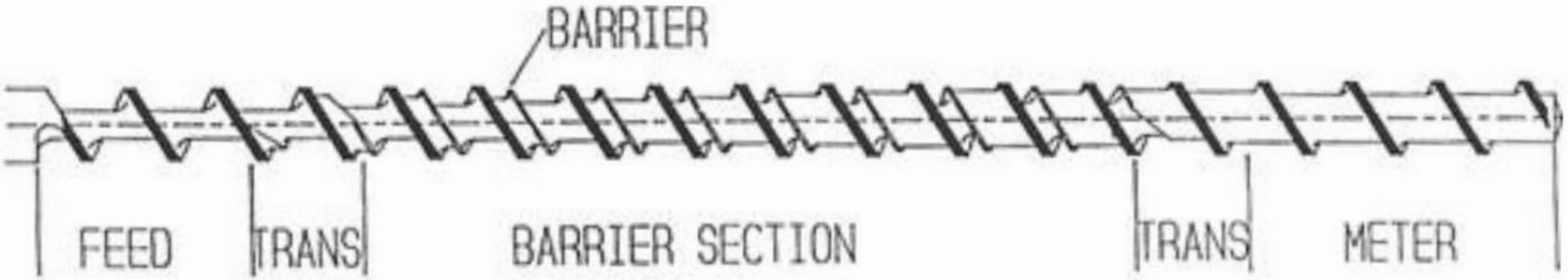
- Increased melting
- At least 80 % is melted by **shear** over the solid bed (i.e. very little conductive melting)

MAILLEFER BARRIER SCREW, solids channel reduces in width , melt channel increases, melting is better, but not optimal due to solid width reduction





Maillefer / UNIROYAL BARRIER SCREW (Reducing Width)



PARALLEL FLIGHT BARRIER SCREW (constant width)

Known also as MC3 or Hartig Barr Screw

The melting capacity of the MC3 Screw (parallel flight, constant width) is significantly higher than that of the Uniroyal/Maillefer screw (traveling flight, reducing width) since the surface area for melting is larger (by a factor of about ~ 1.3)

MIXING SECTIONS

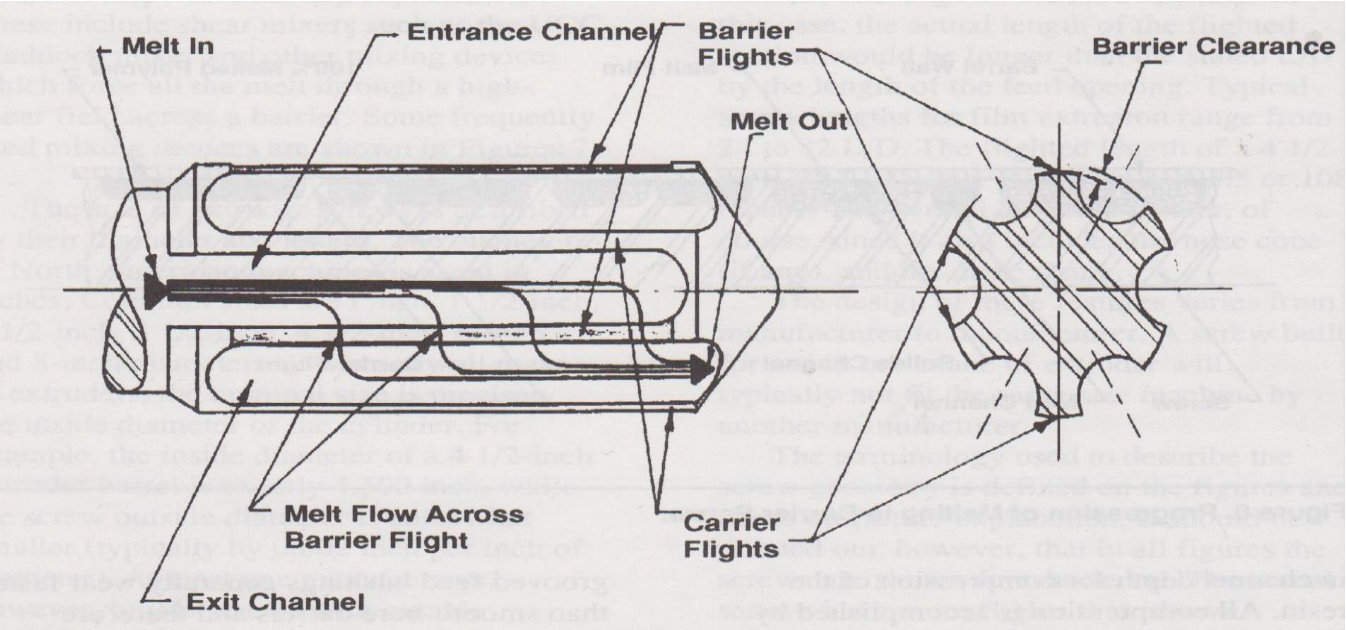
- **Single screw extruders (SSE) are melting and pumping machines, but they do virtually**

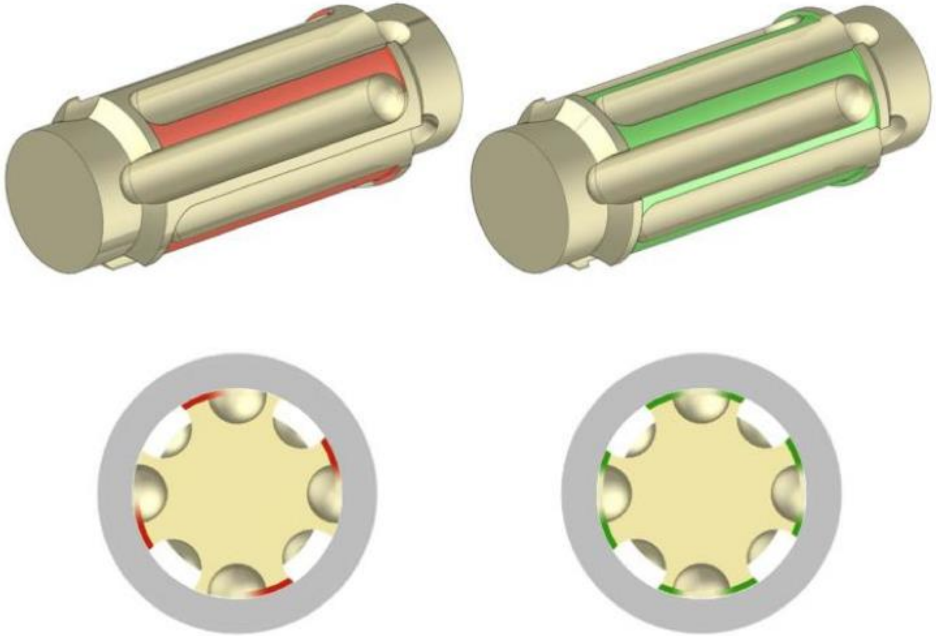
NO DISPERSIVE MIXING and only

LIMITED DISTRIBUTIVE MIXING

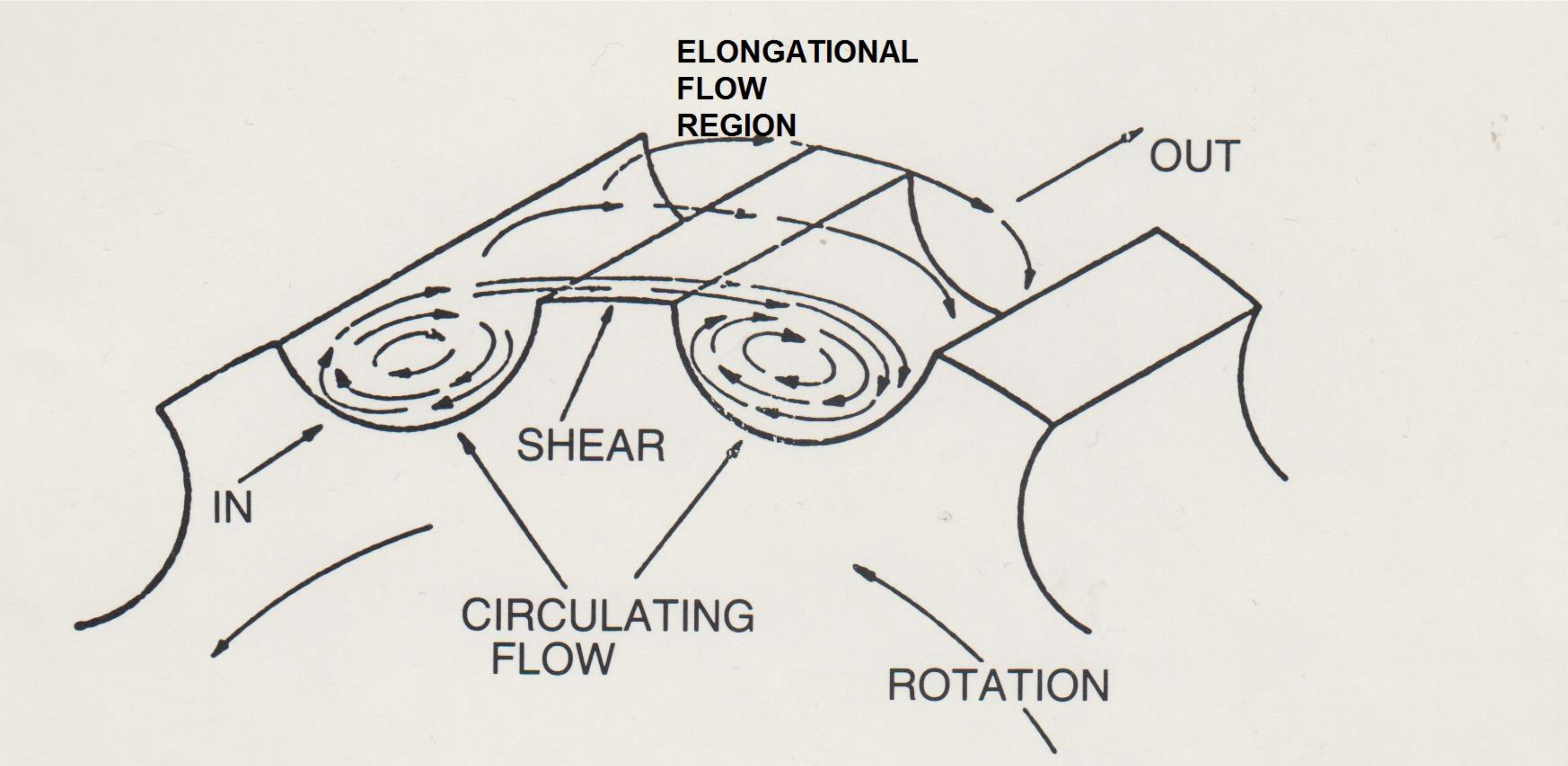
- **MIXING SECTIONS ARE NEEDED**

MADDOCK MIXER (distributive and dispersive mixing)

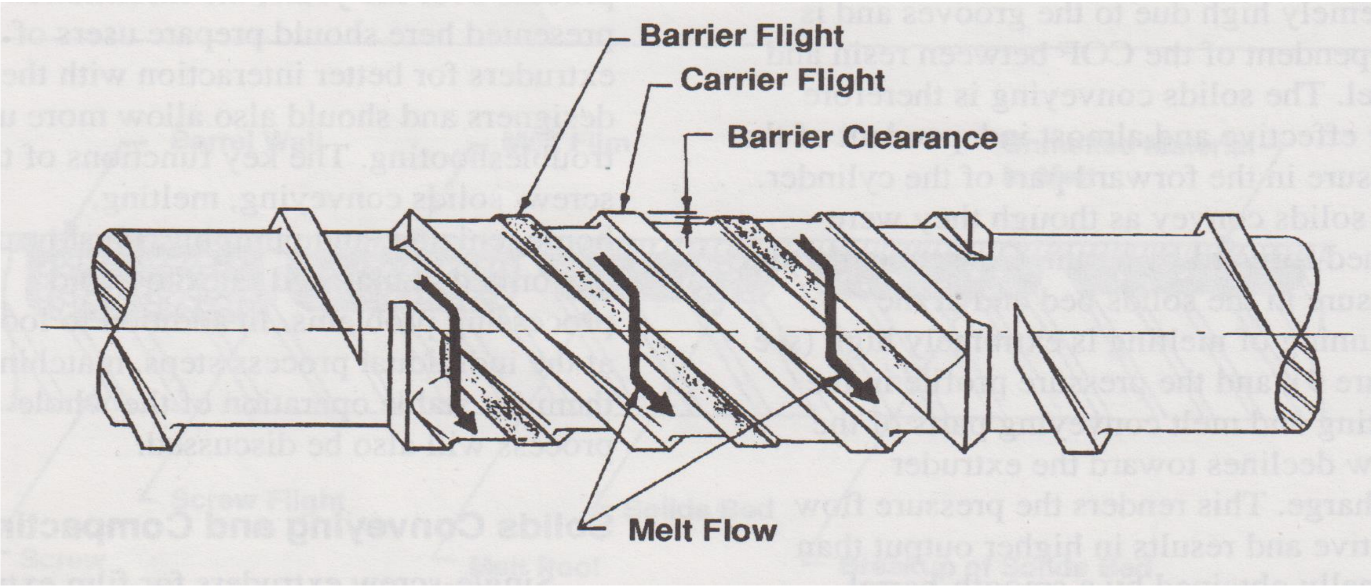




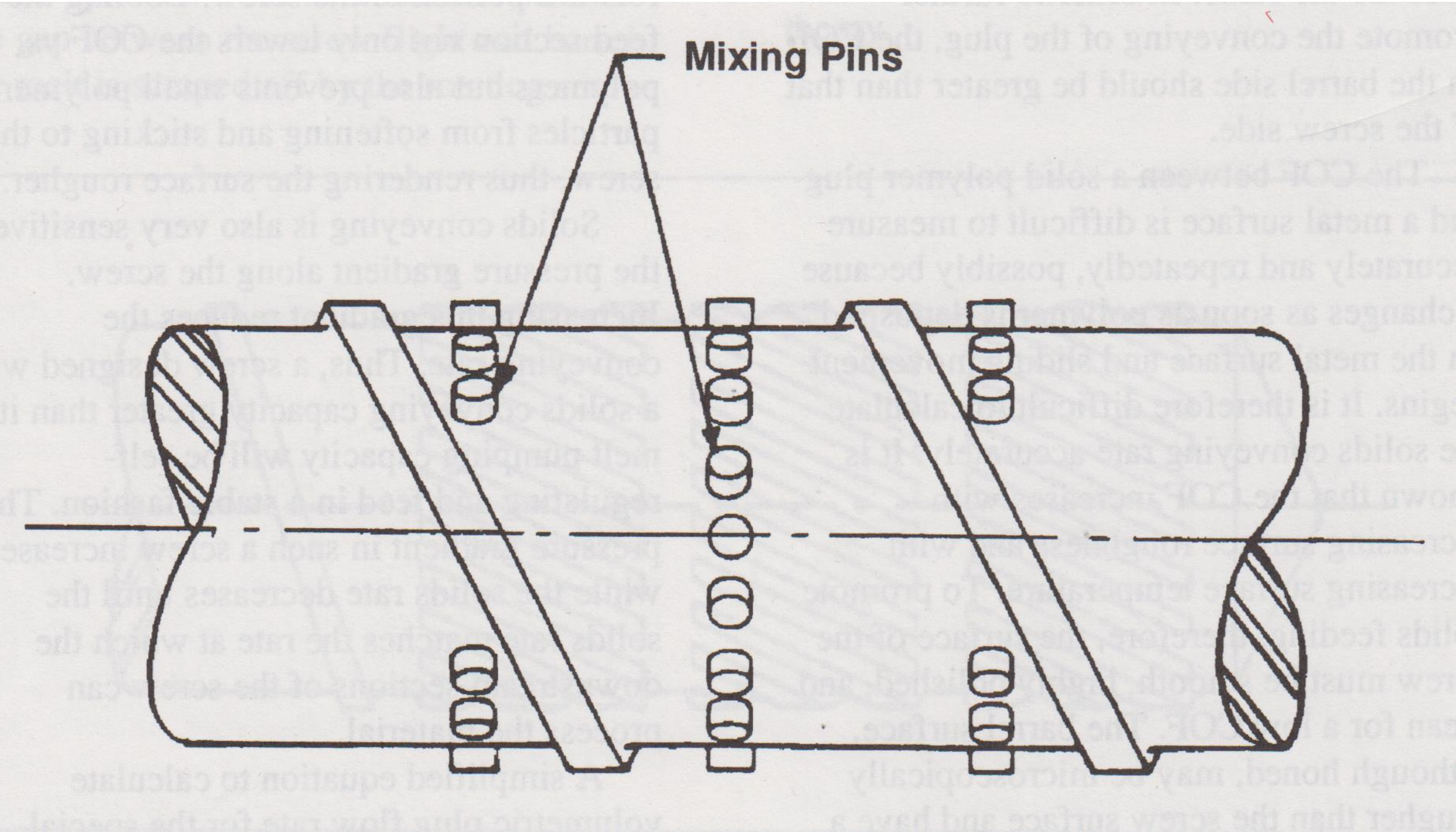
MADDOCK MIXER (showing the regions of **shear, elongation and recirculation)**



EGAN MIXER, distributive and dispersive



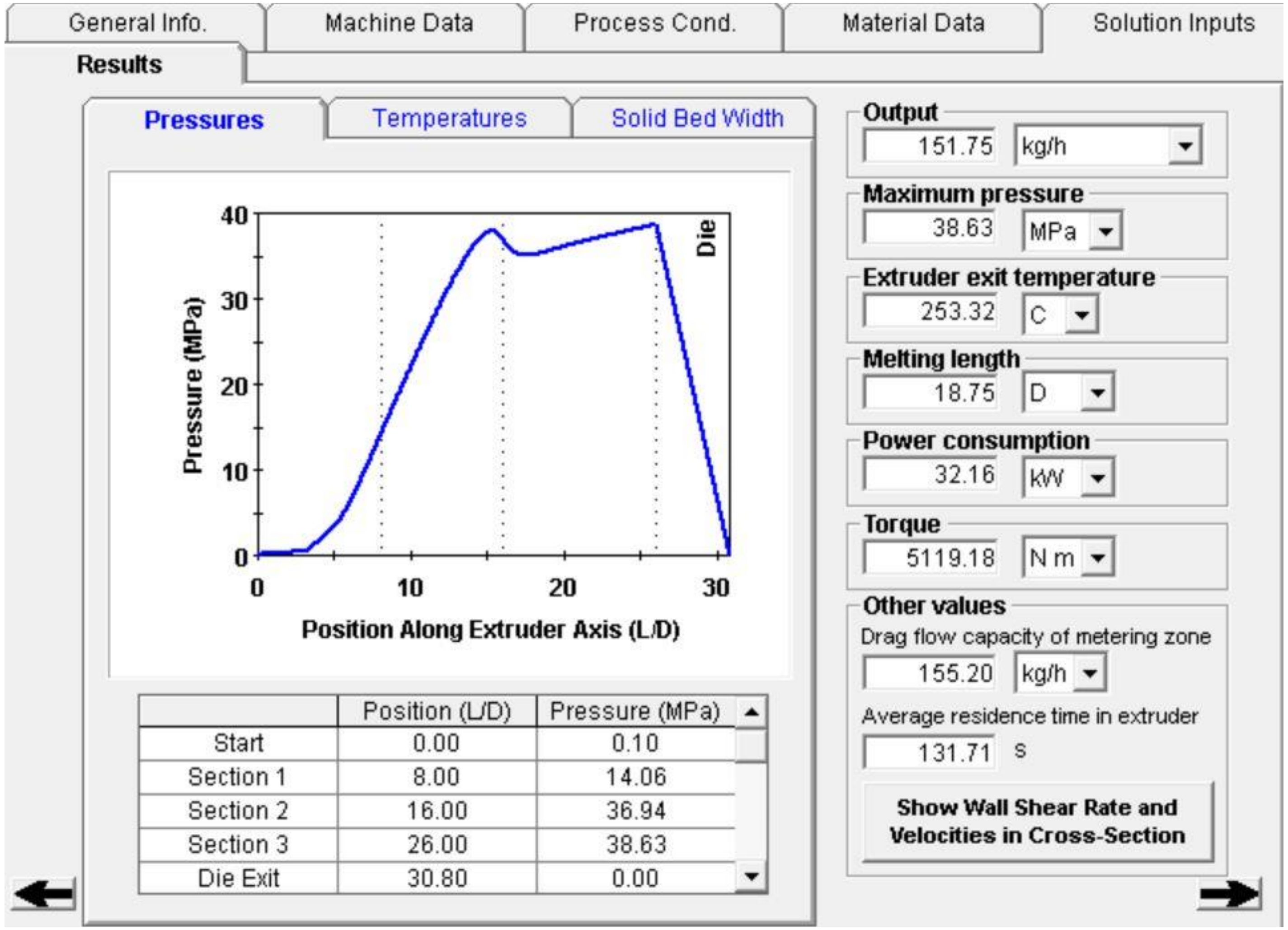
PIN MIXING SECTION (distributive)



Greatest problems in screw extrusion:

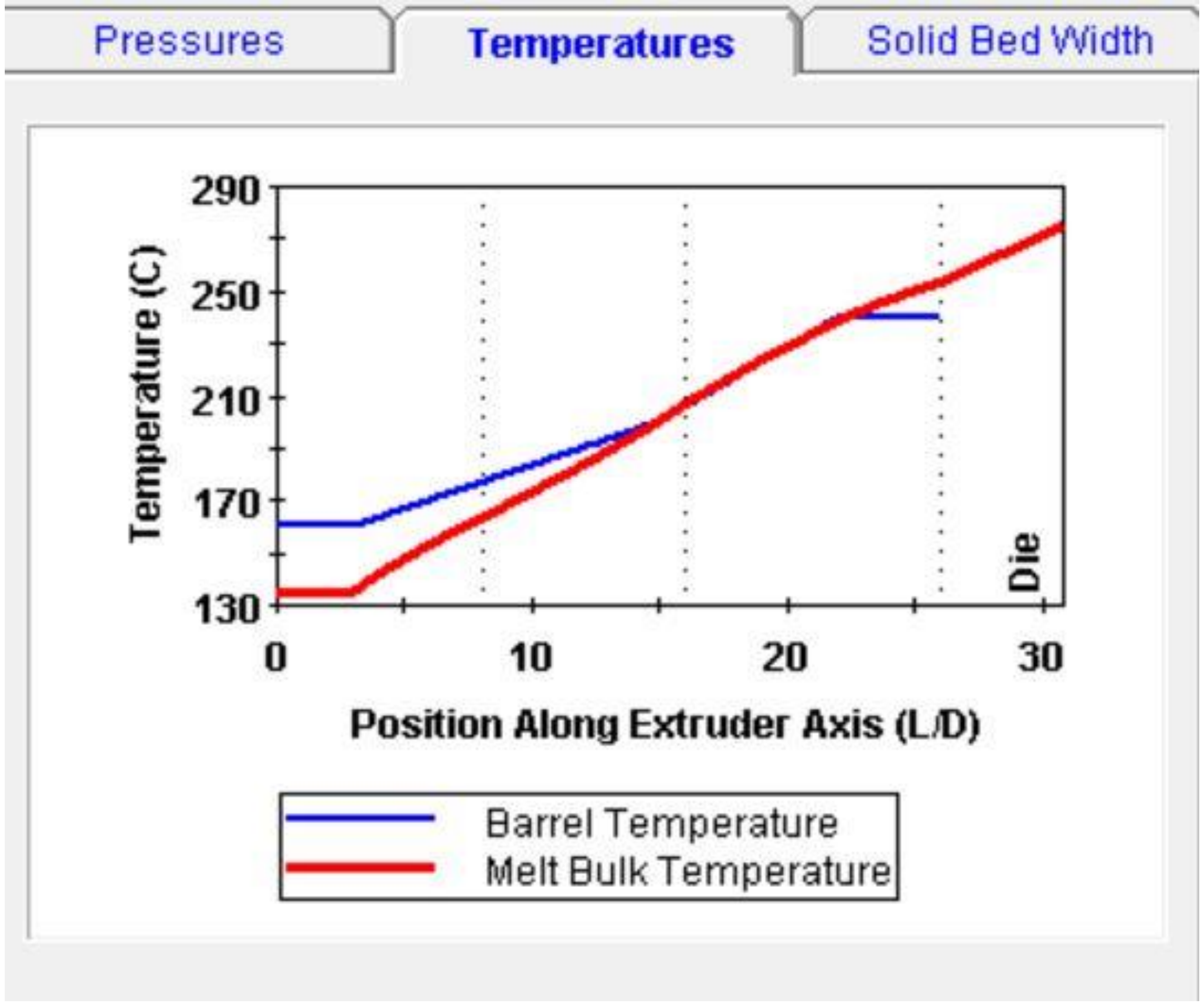
- Unmelted polymer at the end of the screw
- Poorly mixed materials
- Degradation

NEXTRUCAD simulation 100mm screw, L/D=26, compression 3:1 ,60RPM

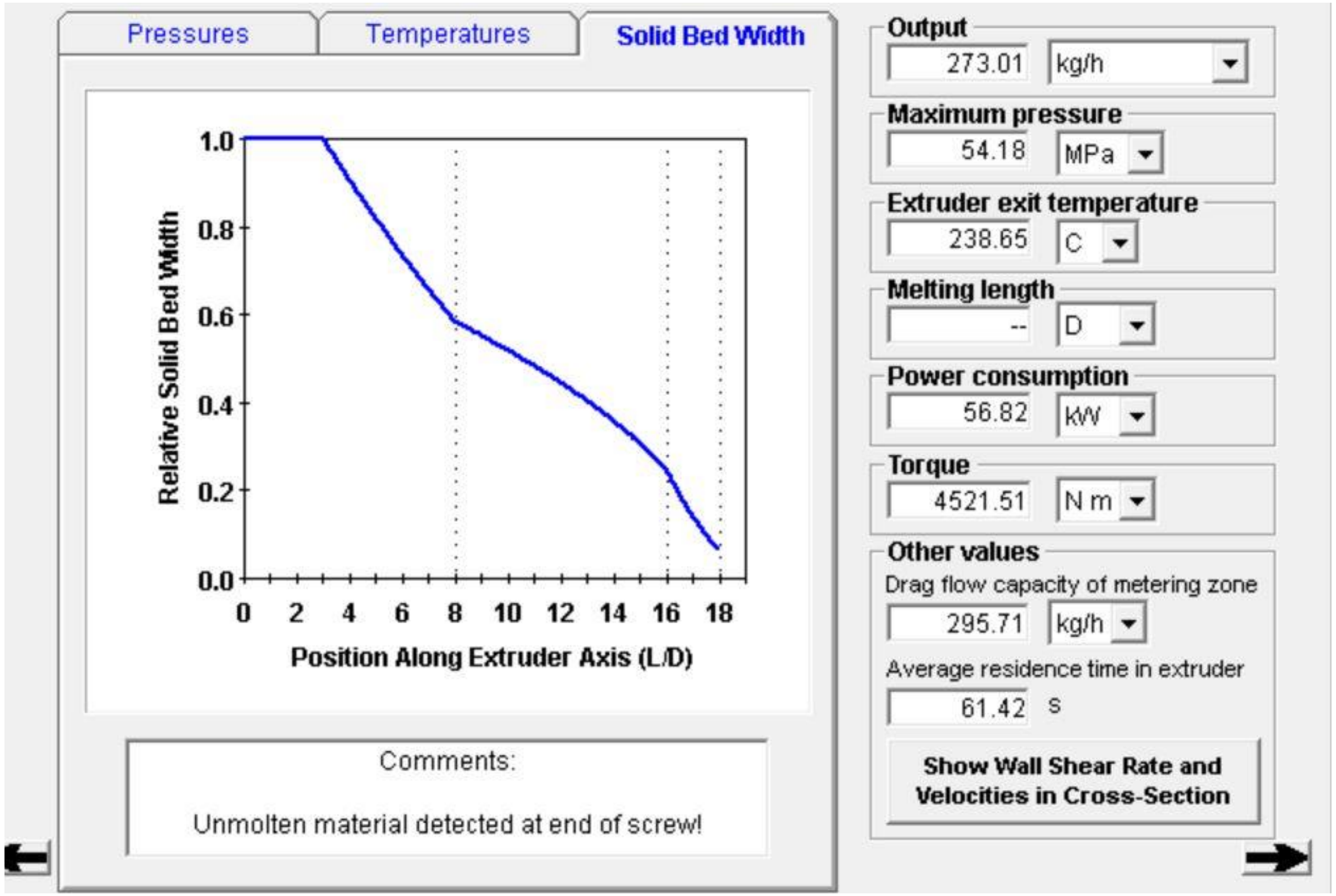


	Position (L/D)	Pressure (MPa)
Start	0.00	0.10
Section 1	8.00	14.06
Section 2	16.00	36.94
Section 3	26.00	38.63
Die Exit	30.80	0.00

NEXTRUCAD simulation 100mm screw, L/D=26,compression 3:1 ,60RPM (appendix example)



NEXTRUCAD simulation 100mm screw, L/D=18,compression 2:1 ,120RPM



EXTRUDER COMPUTER SIMULATION

- **Much more difficult than injection molding cavity filling simulations, because we deal with transport of solid pellets and melting, rather than just melt flow**

- **Greatest advantage of software:**

you can easily try
WHAT IF