Fundamentals of Extrusion/Compounding

Melting Mechanisms: Single vs. Co-rotating Twin-screw Extruders

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Melting Mechanisms: Single vs. Co-rotating Twin-screw Extruders

- Single / Twin-screw compounding system overview

- Single Screw Melting Analysis

- Melting Mechanisms in the Single/Twin-screw Compounder
  - External Thermal Energy Transfer
  - Frictional Heat Build-up / Energy Transfer
  - Mechanical Deformation
  - Melt Stress Transfer
  - Thermal Homogenization

- Influential Variables
  - Machine Design – i.e. screw configuration
  - Process Conditions – Temperature, rpm, rate/rpm
  - Material Characteristics – particle size, Tm, Melt viscosity

- Summary

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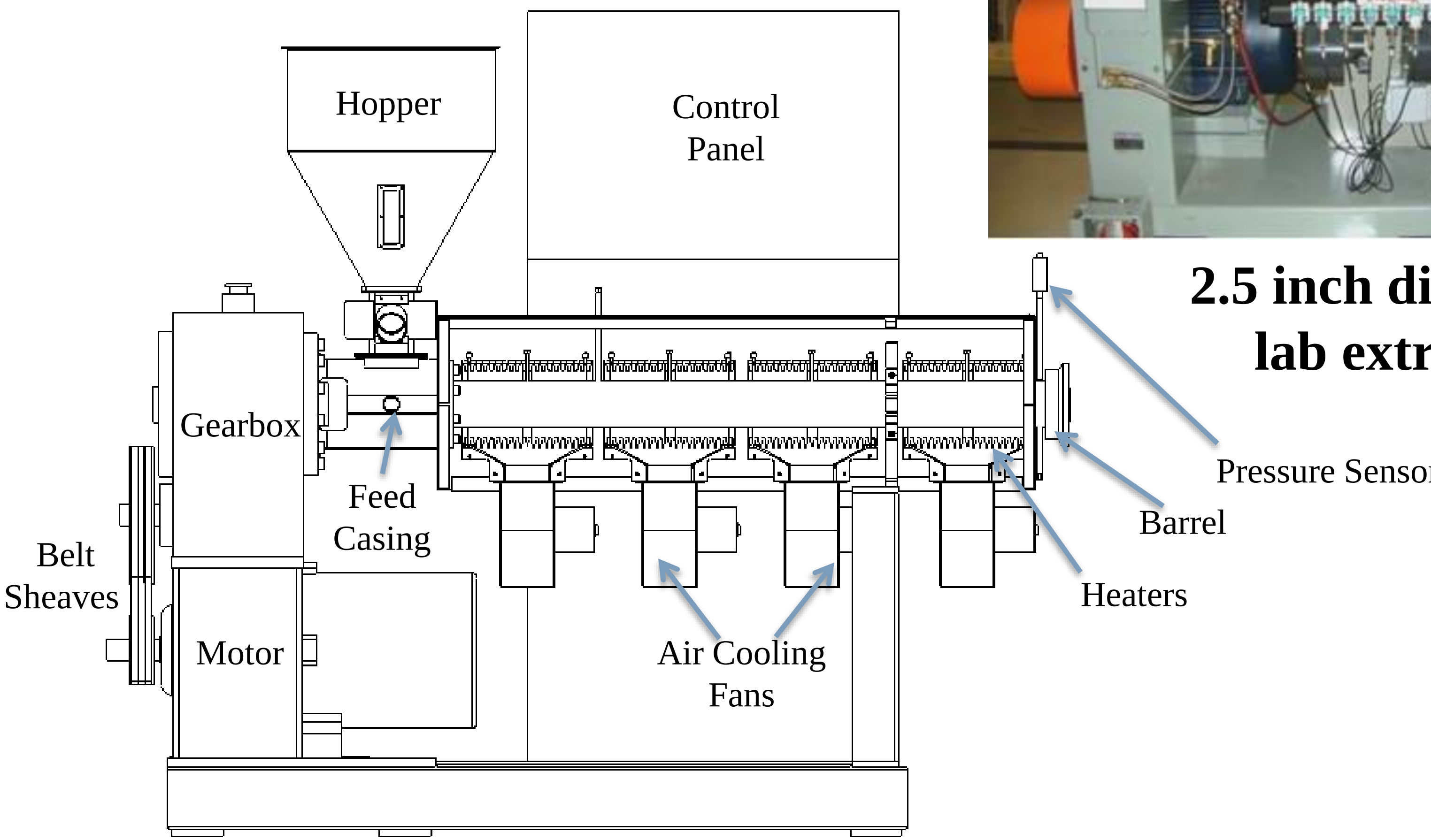
Single-Screw Extruder



2.5 inch diameter lab extruder

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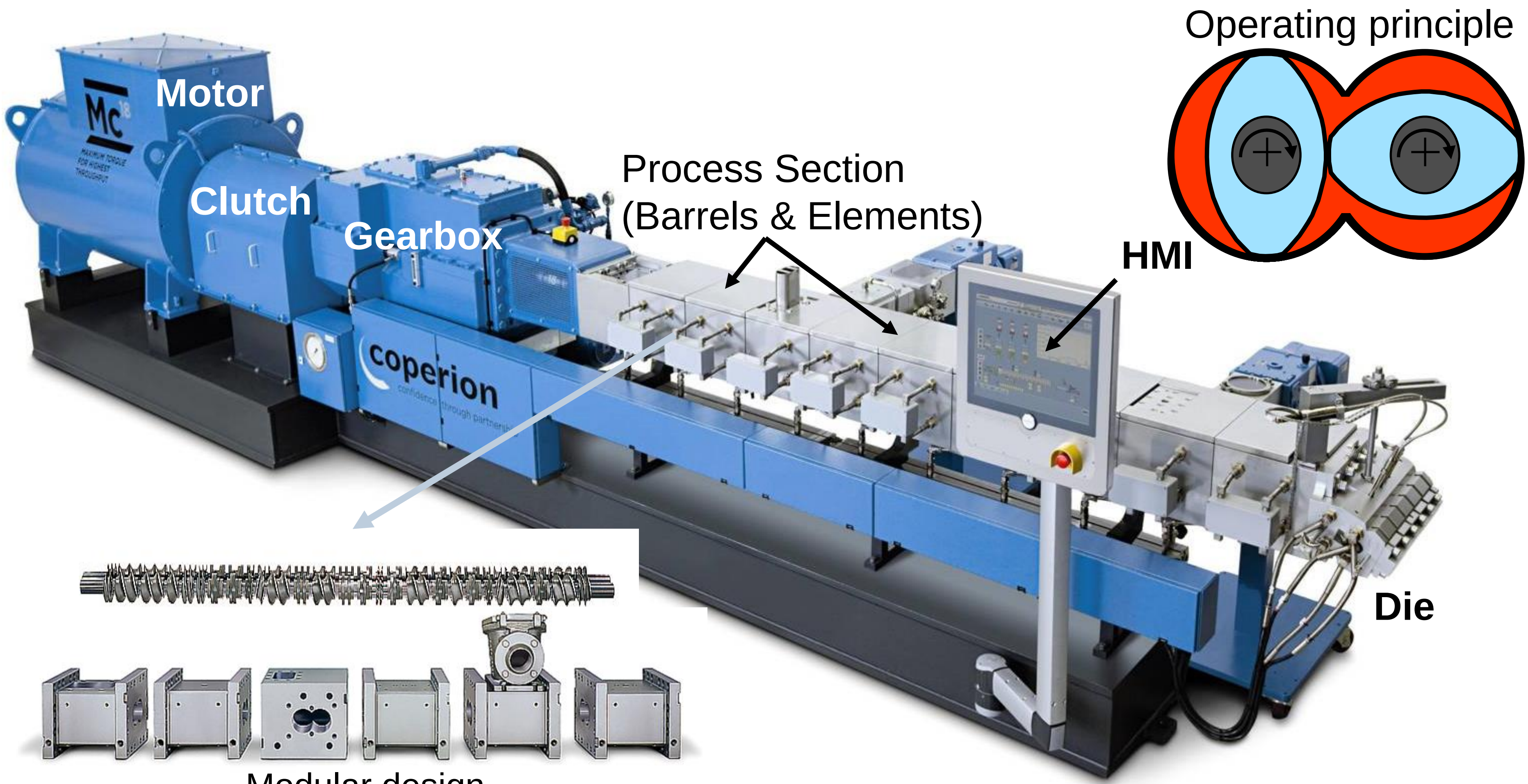
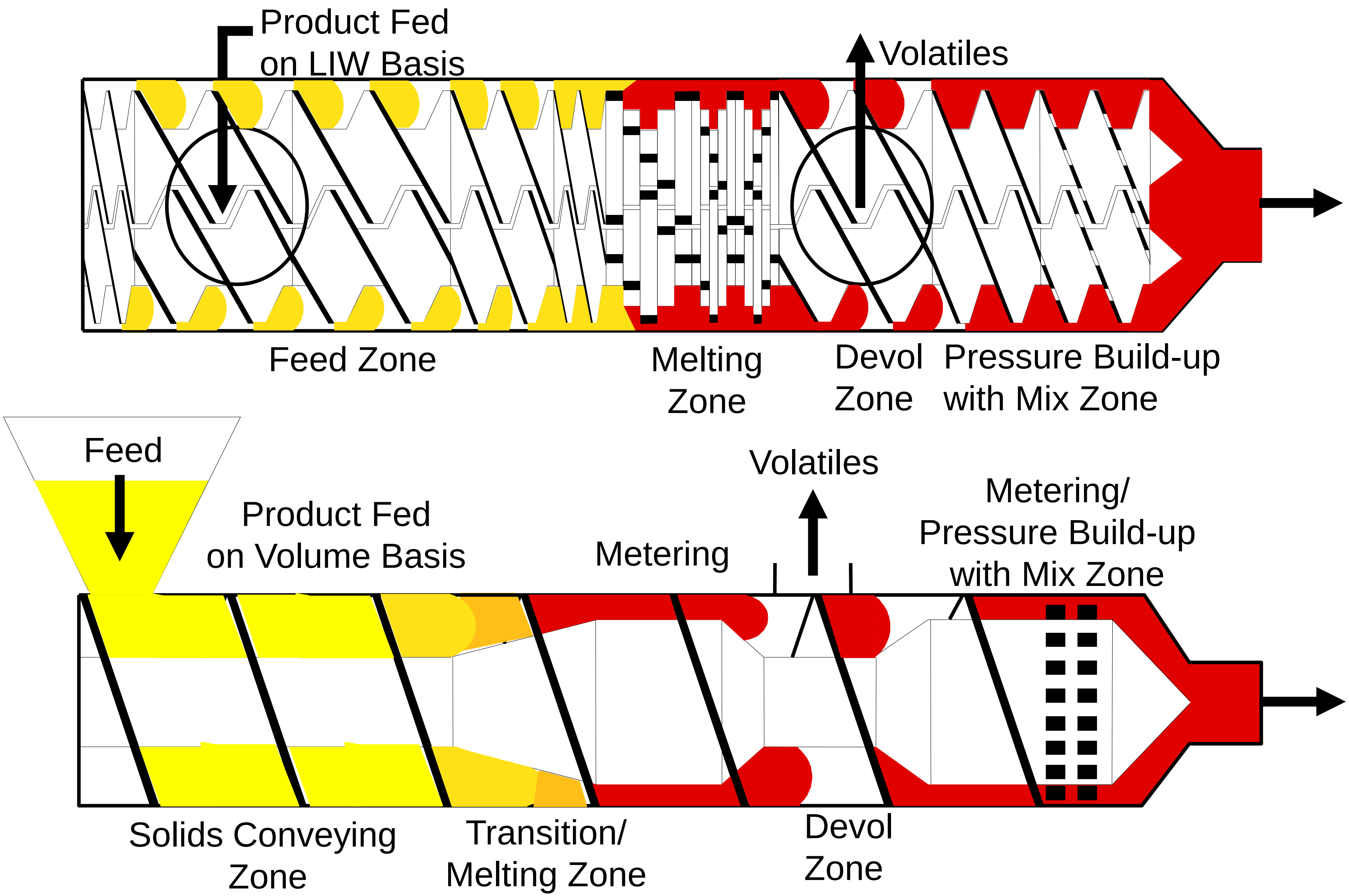
ZSK: Modular Design
Drive power of 10 kW up to 12 MW for rates from 0.5 kg/h and 100 t/h



Modular design
for screw elements and kneading blocks

Comparison of SSE & TSE Mechanisms



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Melting Mechanisms: Single vs. Co-rotating Twin-screw Extruders

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Melting Mechanisms: Single vs. Co-rotating Twin-screw Extruders

Single Screw Melting Analysis Objectives

- Demonstrate Basics of How Single Screw Extruder Melts
  - Initial Heating of Solids
  - Melt Encapsulates solid bed
  - Solid bed melts
    - Heat transfer
    - Viscous dissipation
- Propose new mechanism for solid bed breakup
  - Dispersive Mixers
  - High Tech Screws
- Develop a new model that is consistent with the data analysis
- Impact on Downstream Processing

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- Summary

Solids Conveying

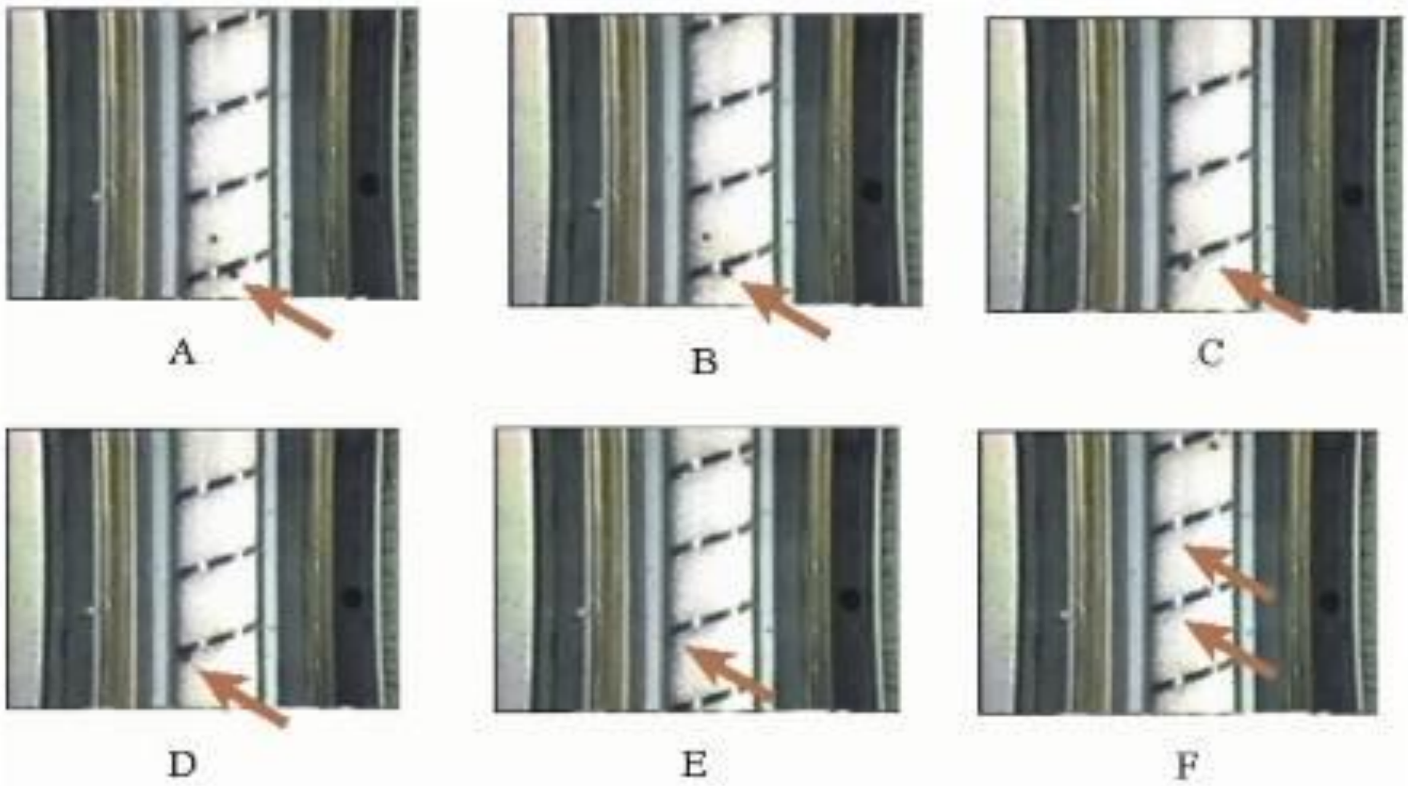
Single Screw

- Not Positive Displacement
- Rate Depends on Friction Force
  - Between Pellets and Barrel
  - Pellets and Screw Surface
- Pellets convey (in general) better than powder
  - Powder convey zone deeper channel
- TPU conveys faster than PE
  - PE convey zone channel depth greater
- No melting desired conveying zone

Twin-Screw

- Combined Non-Positive/Positive Displacement
- Rate Depend on Friction Force
  - Between feedstock and Barrel
  - Between feedstock particles
- Pellets convey (in general) better than powder
  - Powder convey zone greater pitch
  - Powder convey zone greater l/d
- No melting permitted in solids convey zone

Pellets Pushed by Flight in Single Screw



Data taken at Eastman Chemical with the help of Dr. Doug Small
Video available on Extrusion Division Web Site

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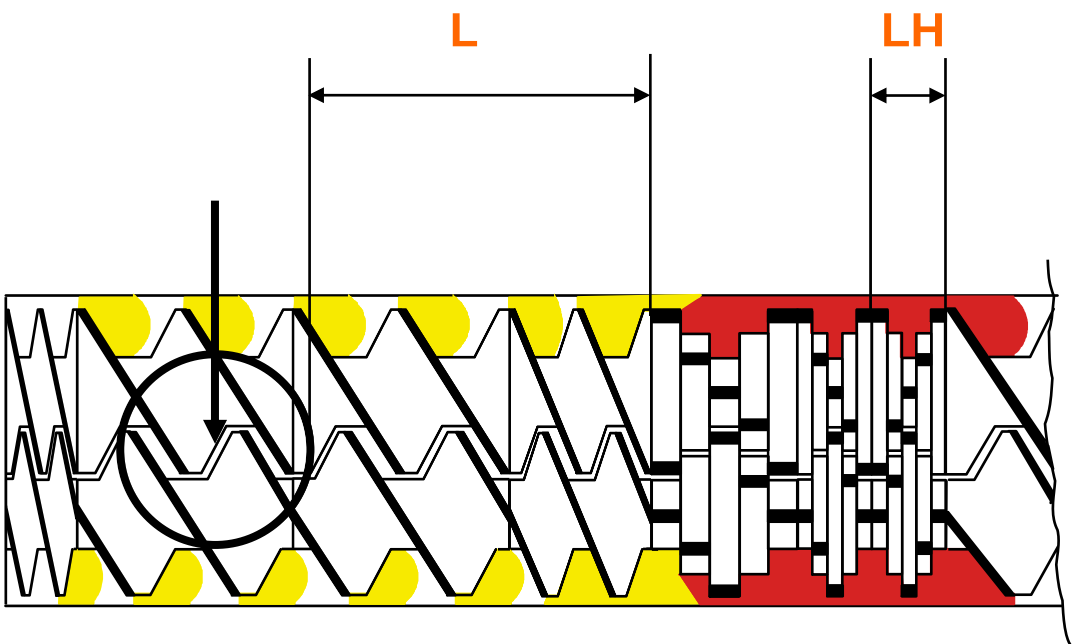
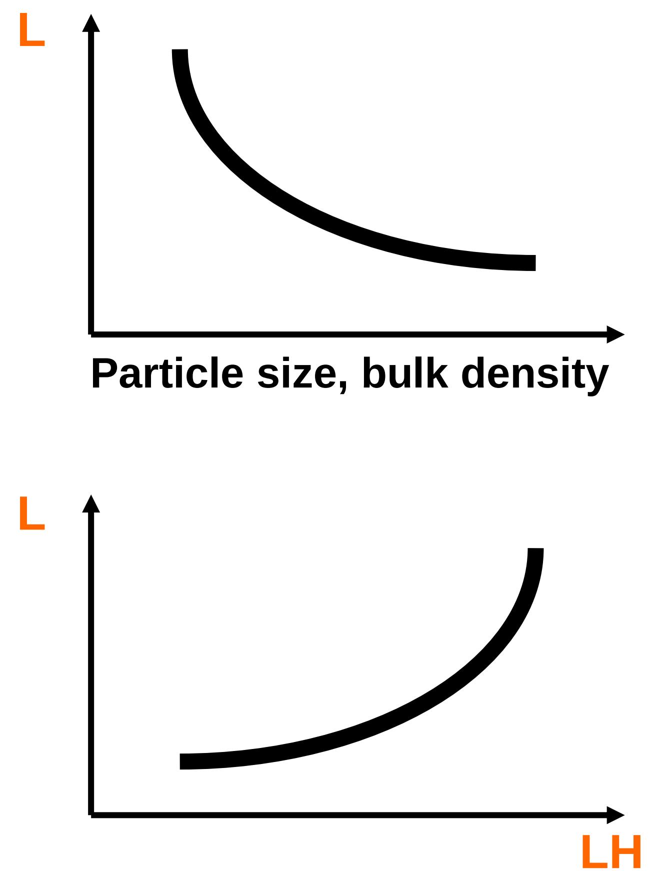
Impact on solids conveying/back up before Melting Section of:
a) particle size
b) melting section restrictions





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Solid to Melt Transition:

1) External Energy Transfer
2) Frictional Heat Build-up / Energy Transfer

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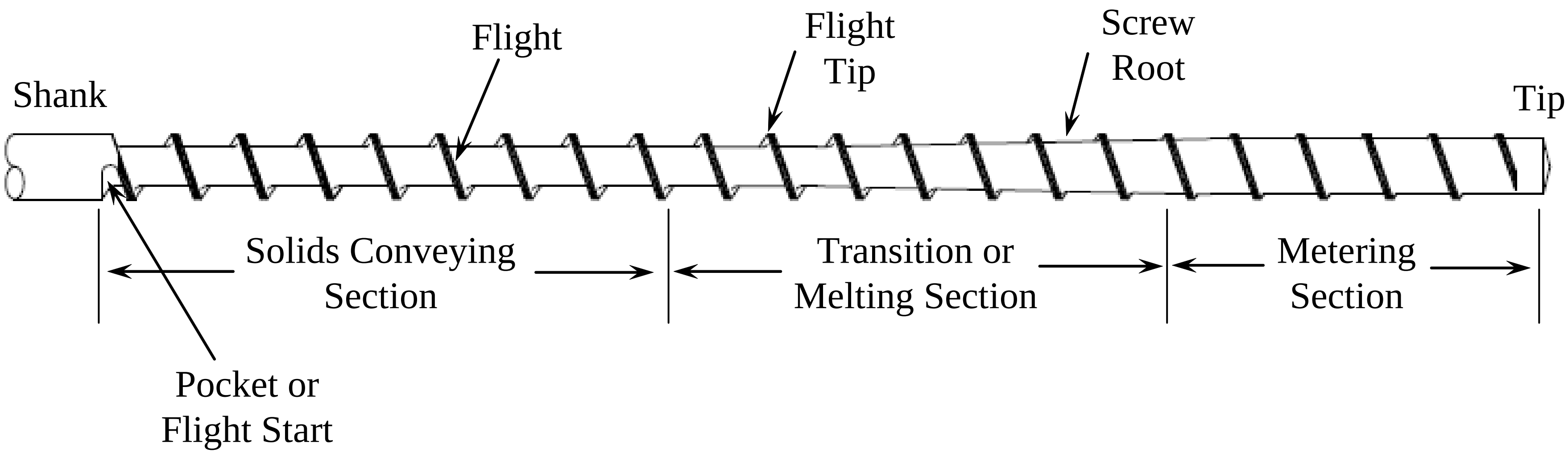
Single Screw Geometric Specifications and Definitions



- Specifications
  - Diameter: 0.75 inch up to 8 inch (larger machines possible)
  - Length-to-Diameter (L/D) Ratio: 8 to 40 (flow path only)
  - Transition-Primary Melting Section
    Core Diameter Increases from Solids Conveying Diameter to
    Metering Diameter

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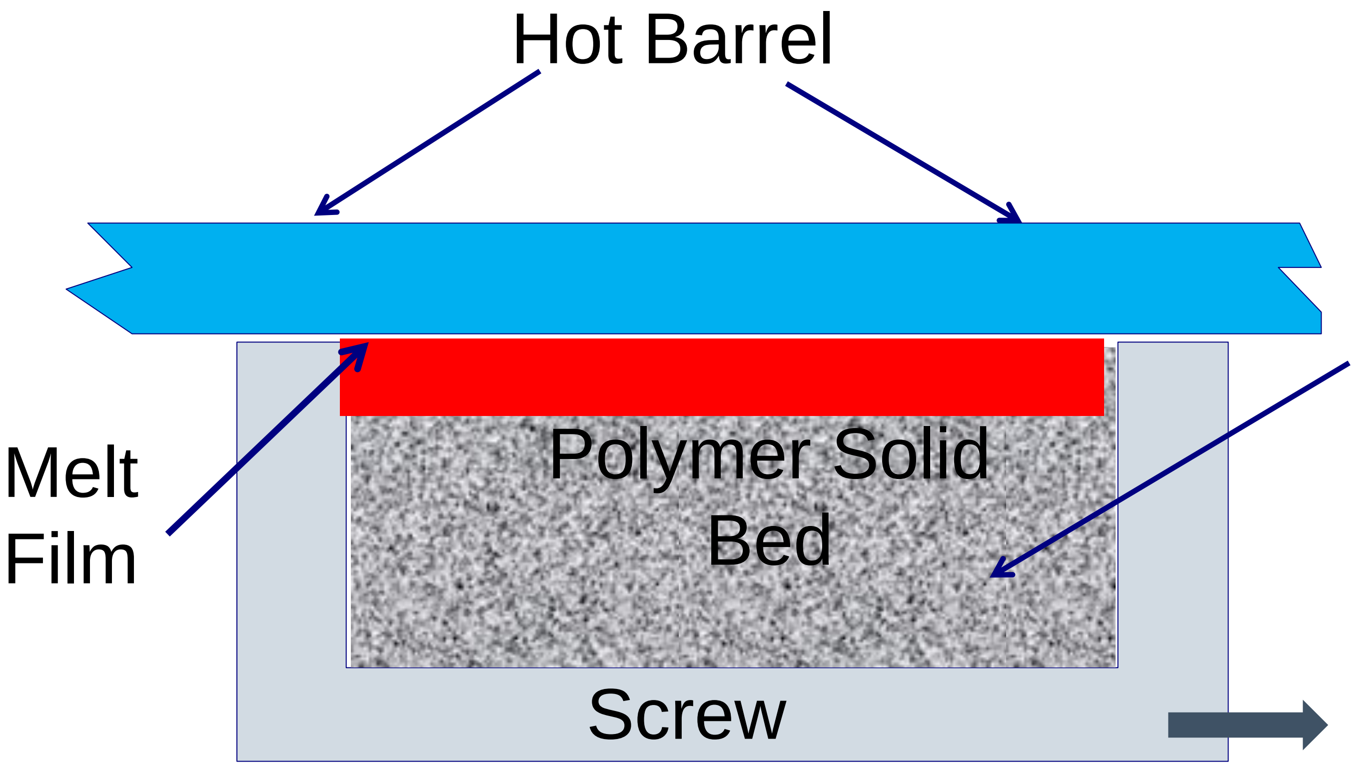
Single Screw: Solid Bed Encapsulation - Reynolds Bearing Effect



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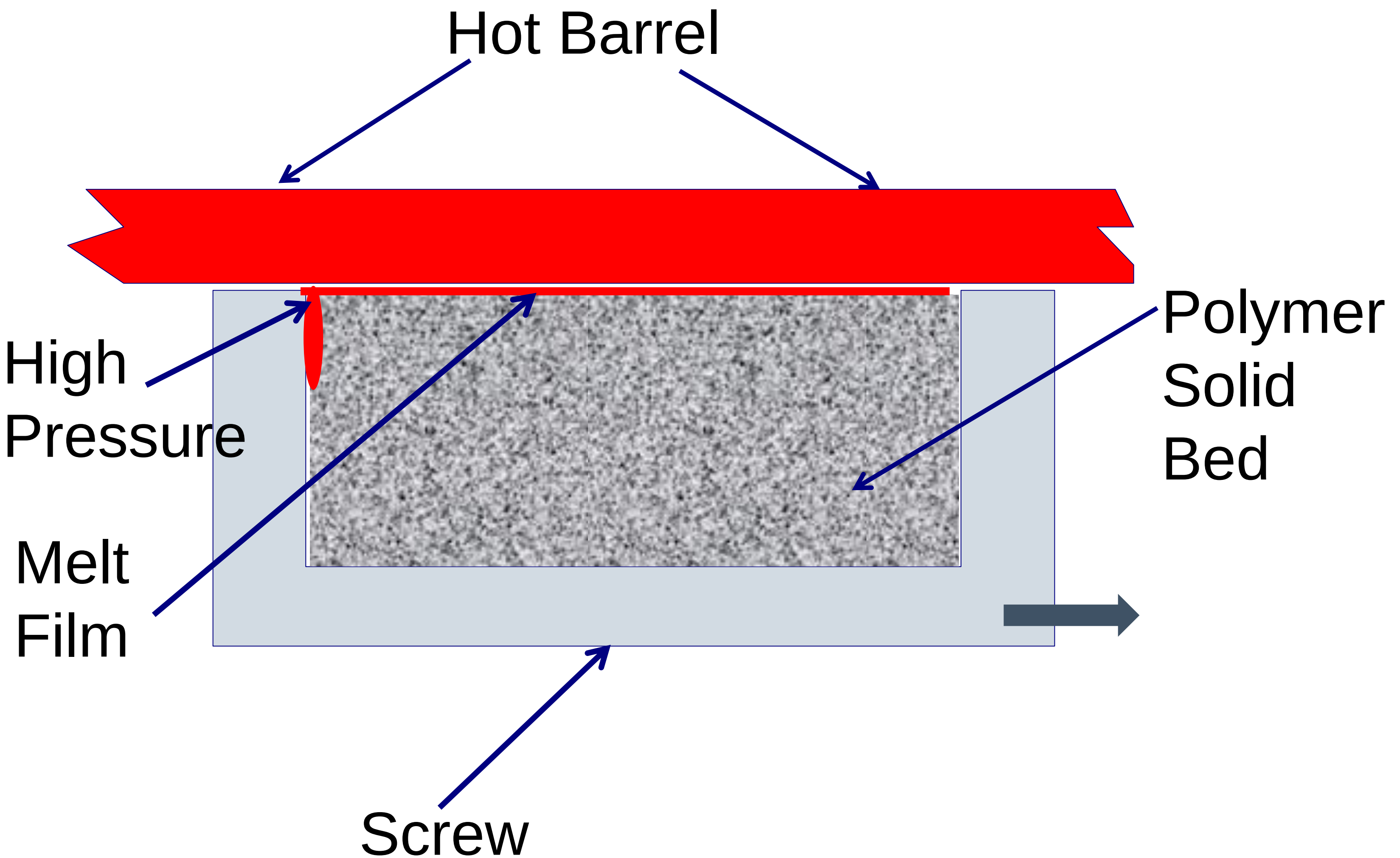
Single Screw: Solid Bed Encapsulation - Reynolds Bearing Effect



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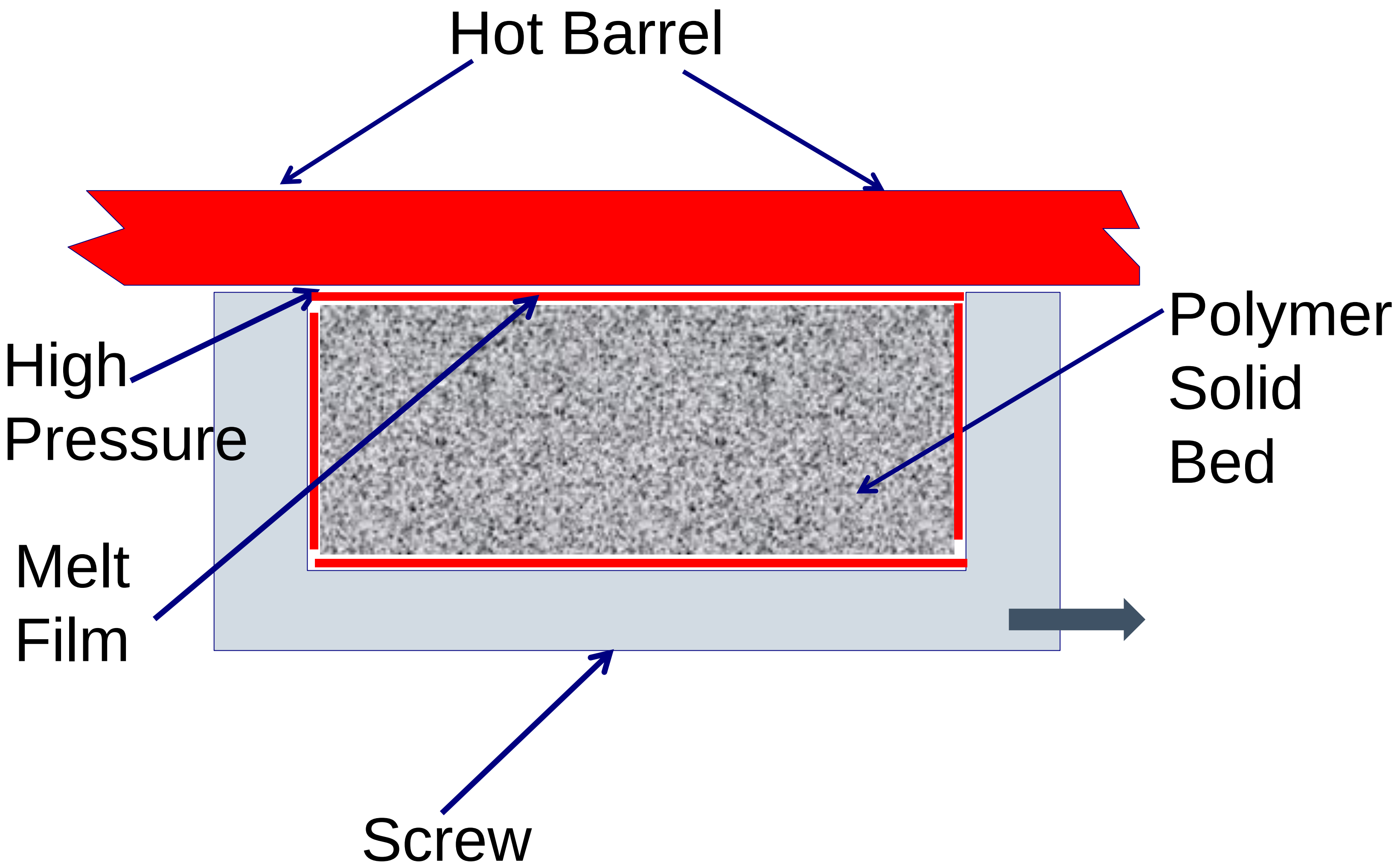
Single Screw: Solid Bed Encapsulation - Reynolds Bearing Effect



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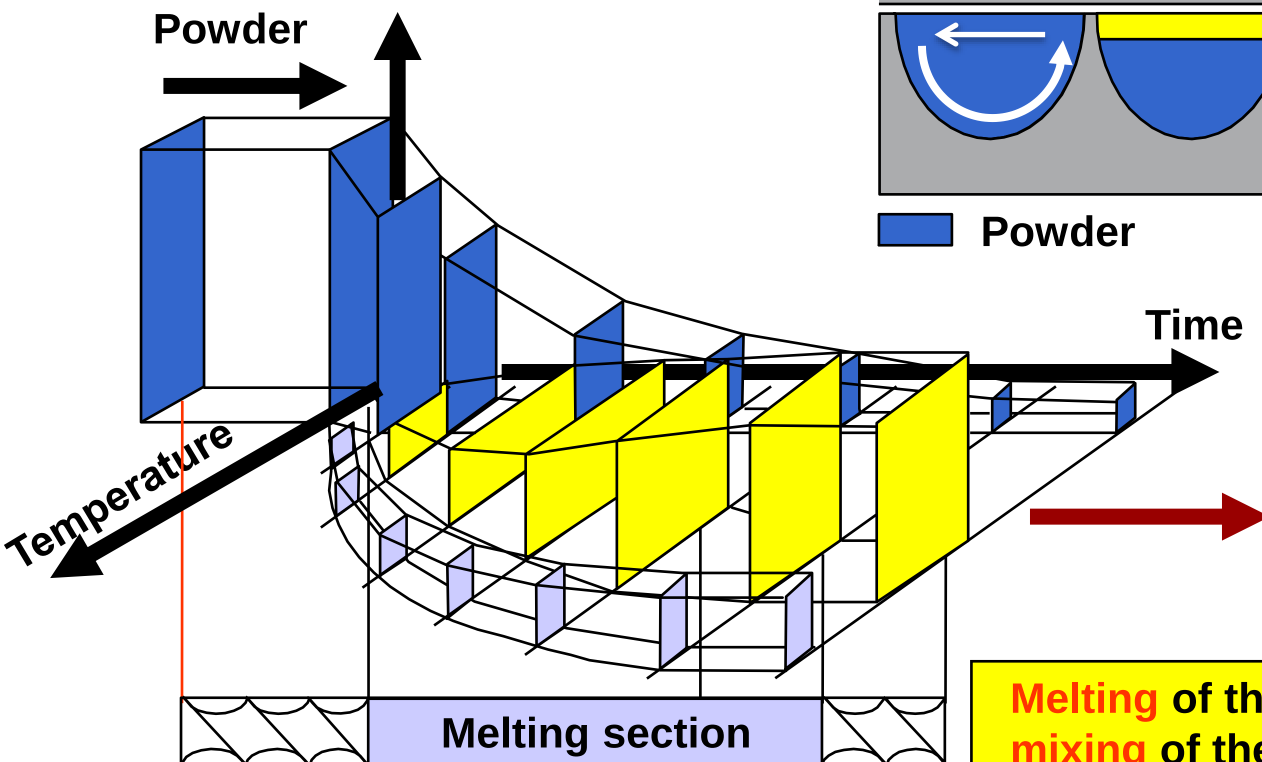
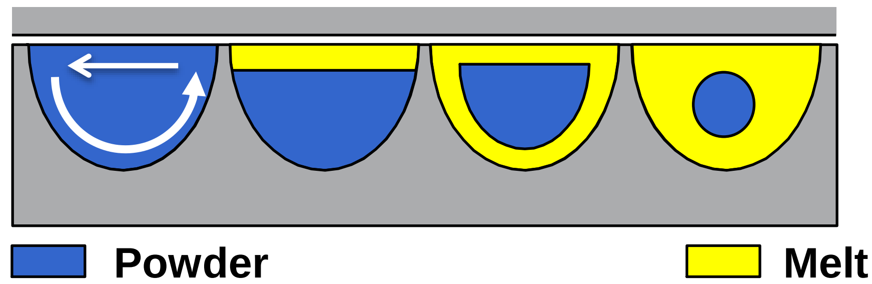
Twin-screw: Melting via External Thermal Energy Transfer
Pitfall: Premelting in Screw Bushings





Inhomogeneous melt with powder clusters

Melting of the powder without immediate mixing of the melt with the remaining powder or mixing of the high and low viscous particles results in an inhomogeneous melt.

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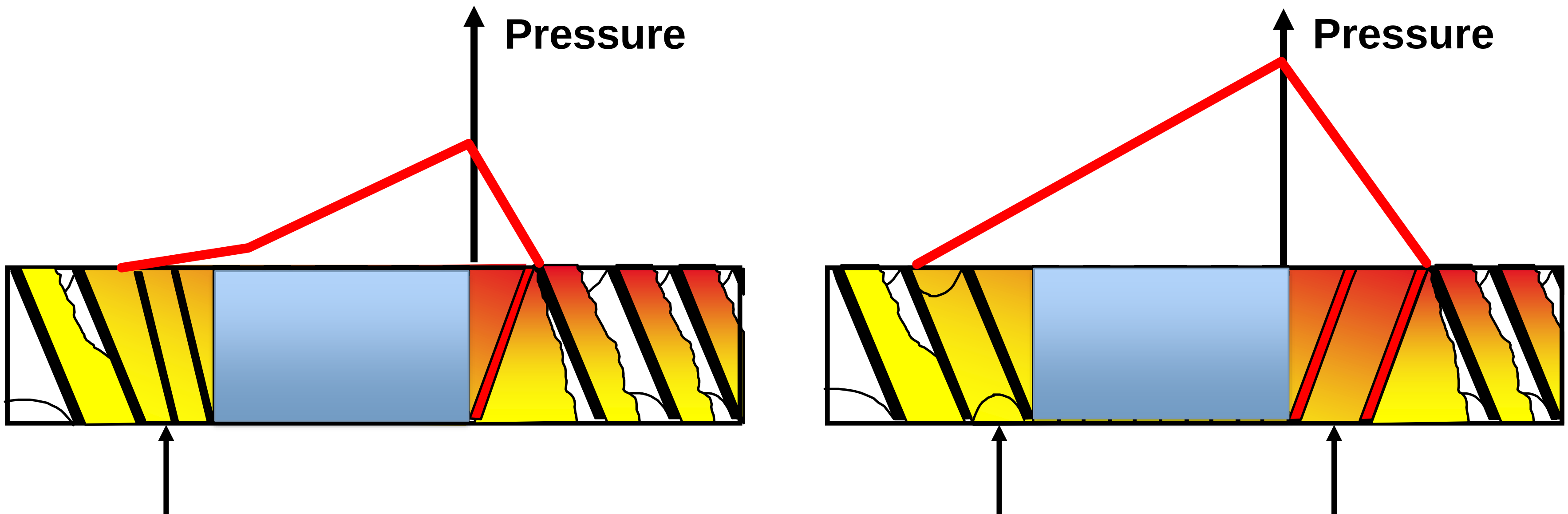
Twin-screw: Melting via Frictional Heat Build-up / Energy Transfer
Pitfall: Material Back up and melt in Screw Bushings



Small pitch element is 100% filled. Compressed powder/low Tm pellets start to melt at the due to frictional heat generation and/or hot barrel surface.	Left-handed elements backing-up the feedstock into the conveying section. The compressed powder/low Tm pellets start to melt due to frictional heat and/or hot barrel surface.

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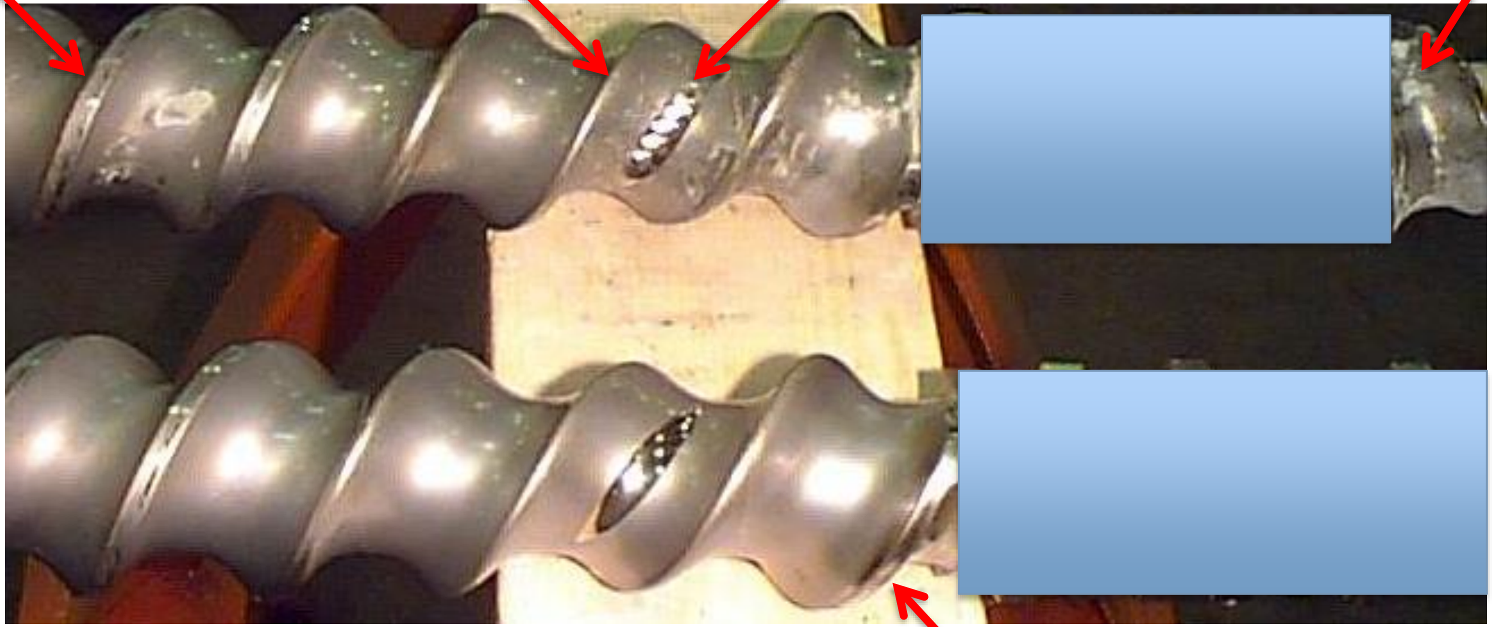
Twin-screw: Frictional Heat Build-up / Energy Transfer Prior to KB
Pitfall: Material Back / Melt in Screw Bushings / Wear (Abrasive Feedstock)



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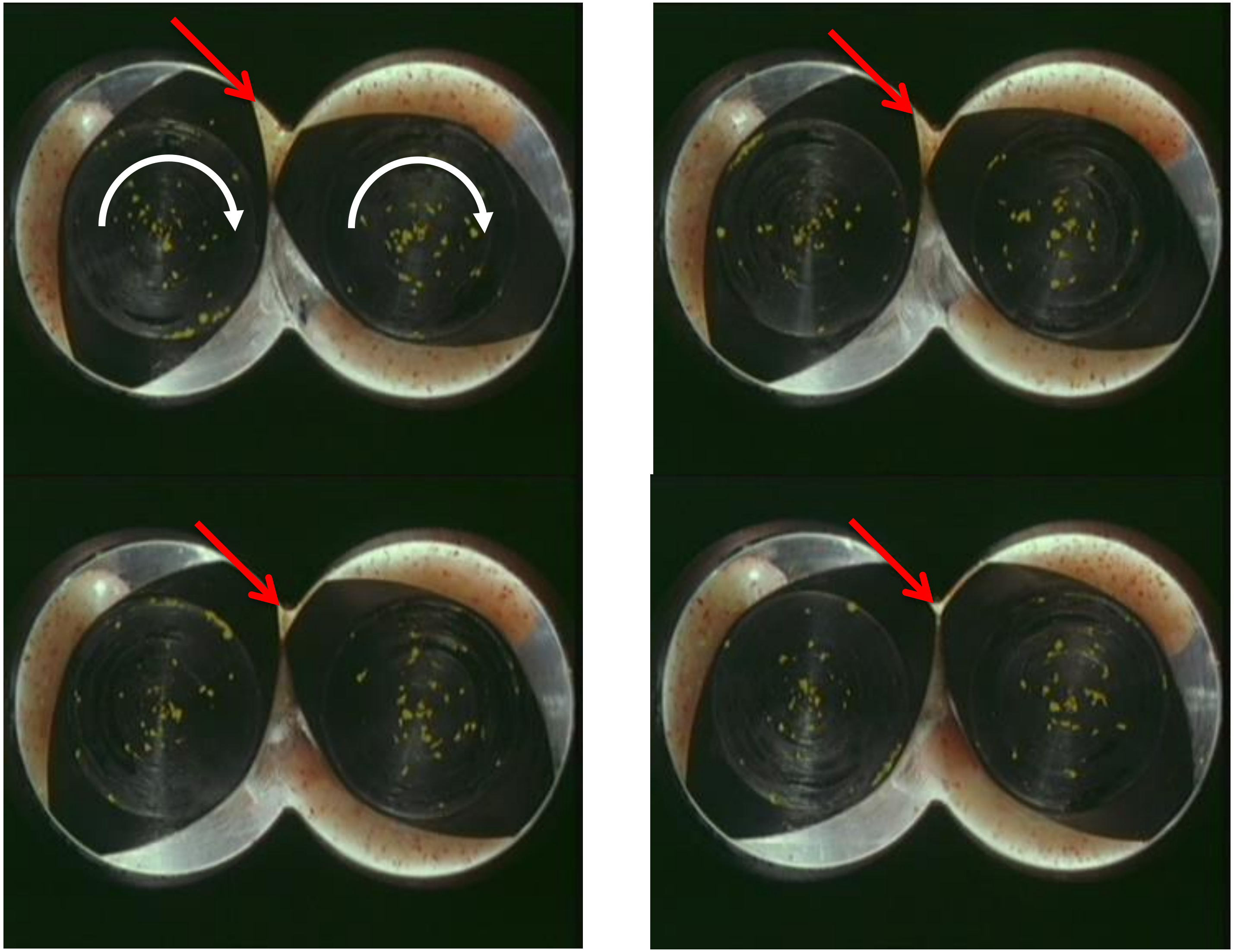
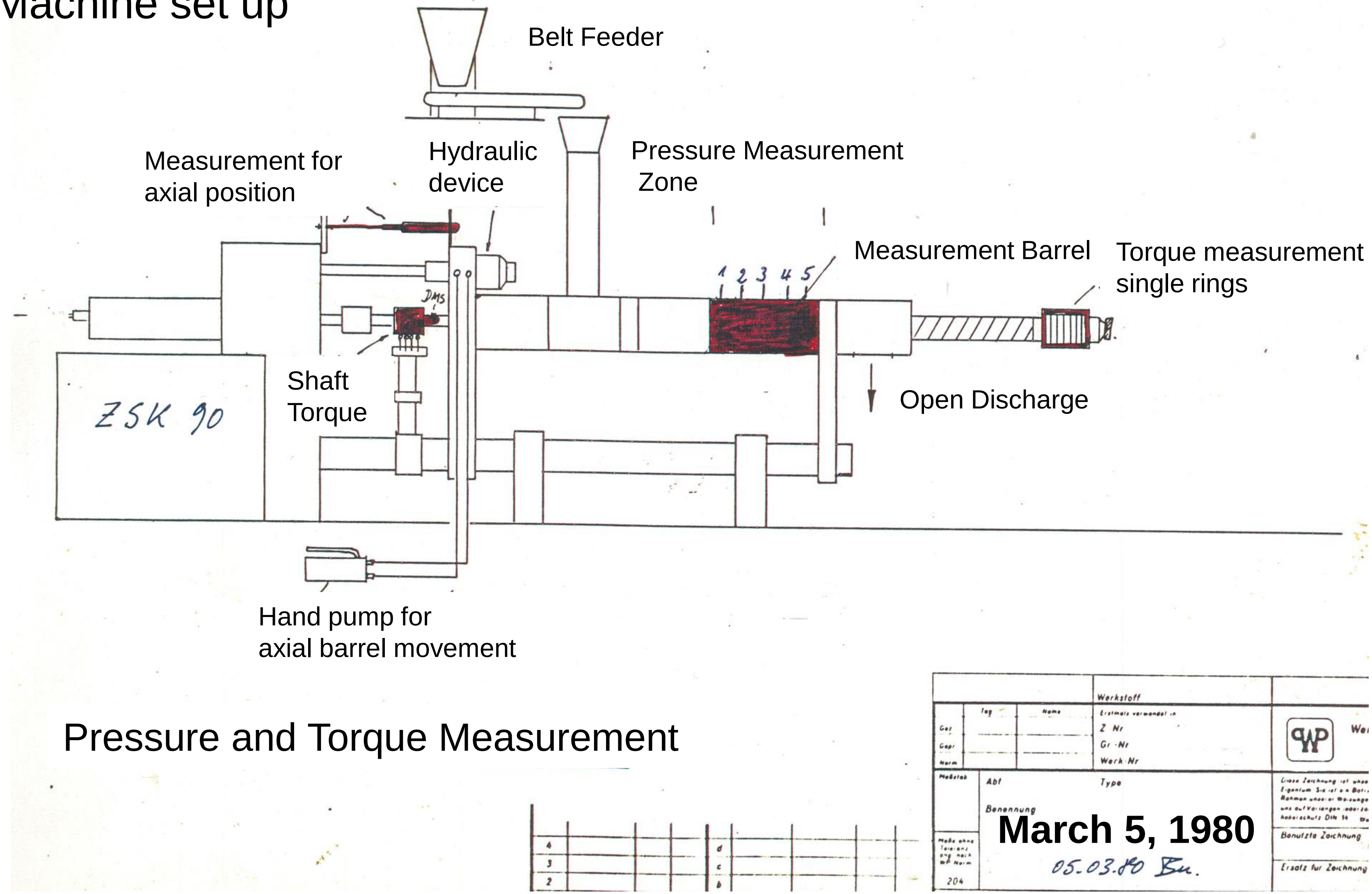
Solid to Melt Transition:

Impact of Mechanical Deformation

Melting via Mechanical Deformation



Melting via Mechanical Deformation Experiments: Machine set up



Pressure and Torque Measurement

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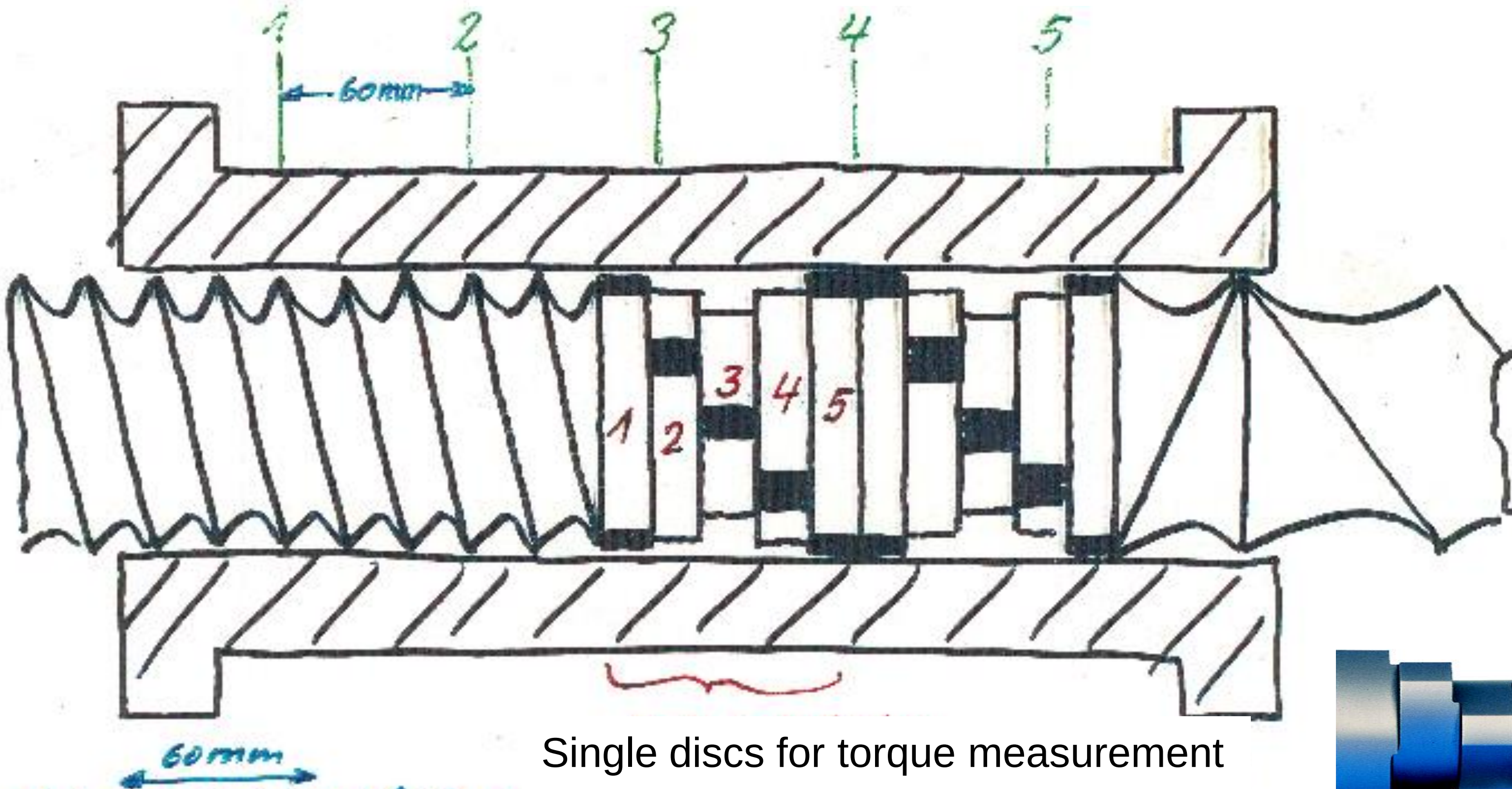
Melting via Mechanical Deformation Experiments: Radial Pressure Measurement vs. Axial Location

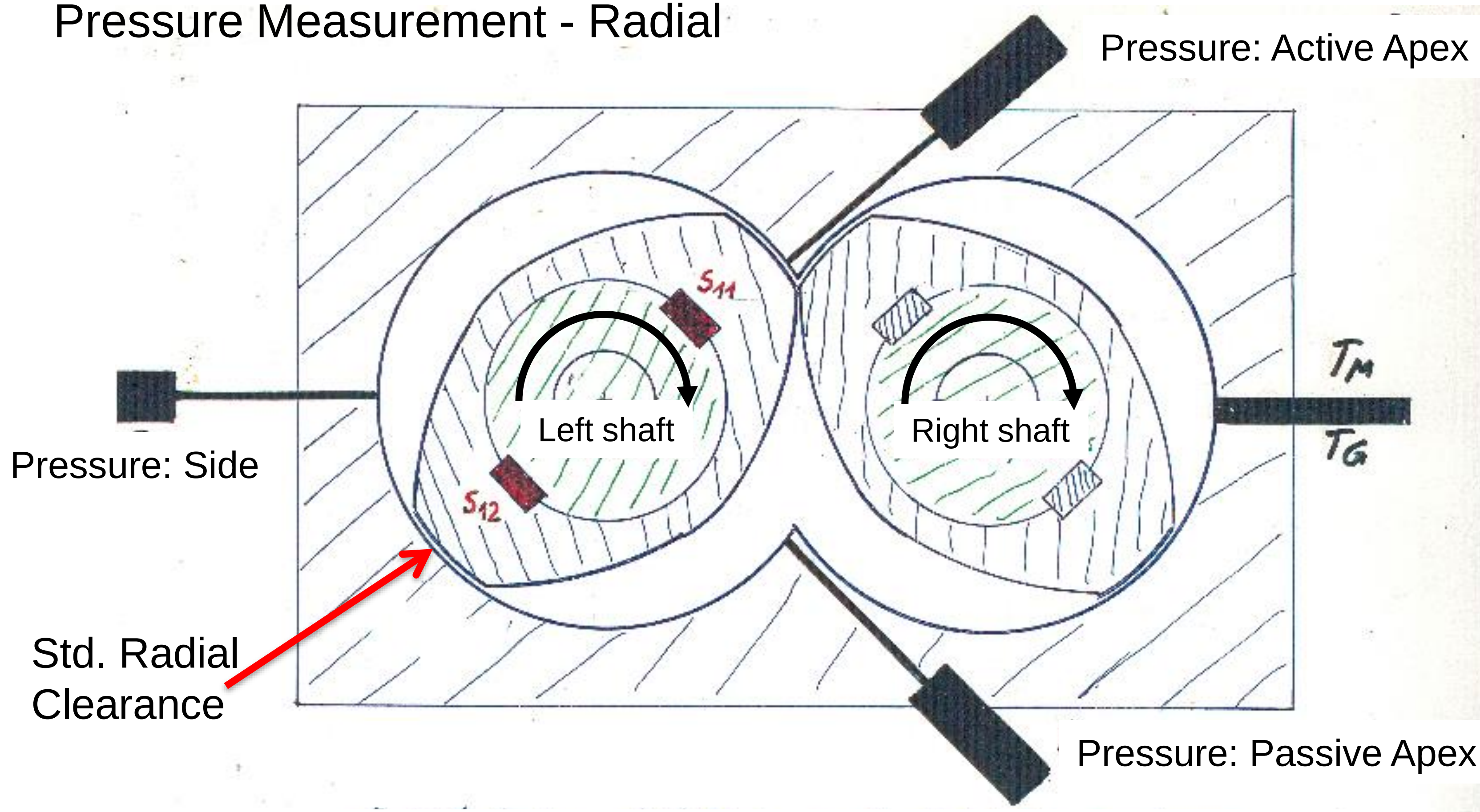
Five measurement points, 3 pressure and 2 temperature



Single discs for torque measurement

Axial movement

Melting Experiments:
Pressure Measurement - Radial



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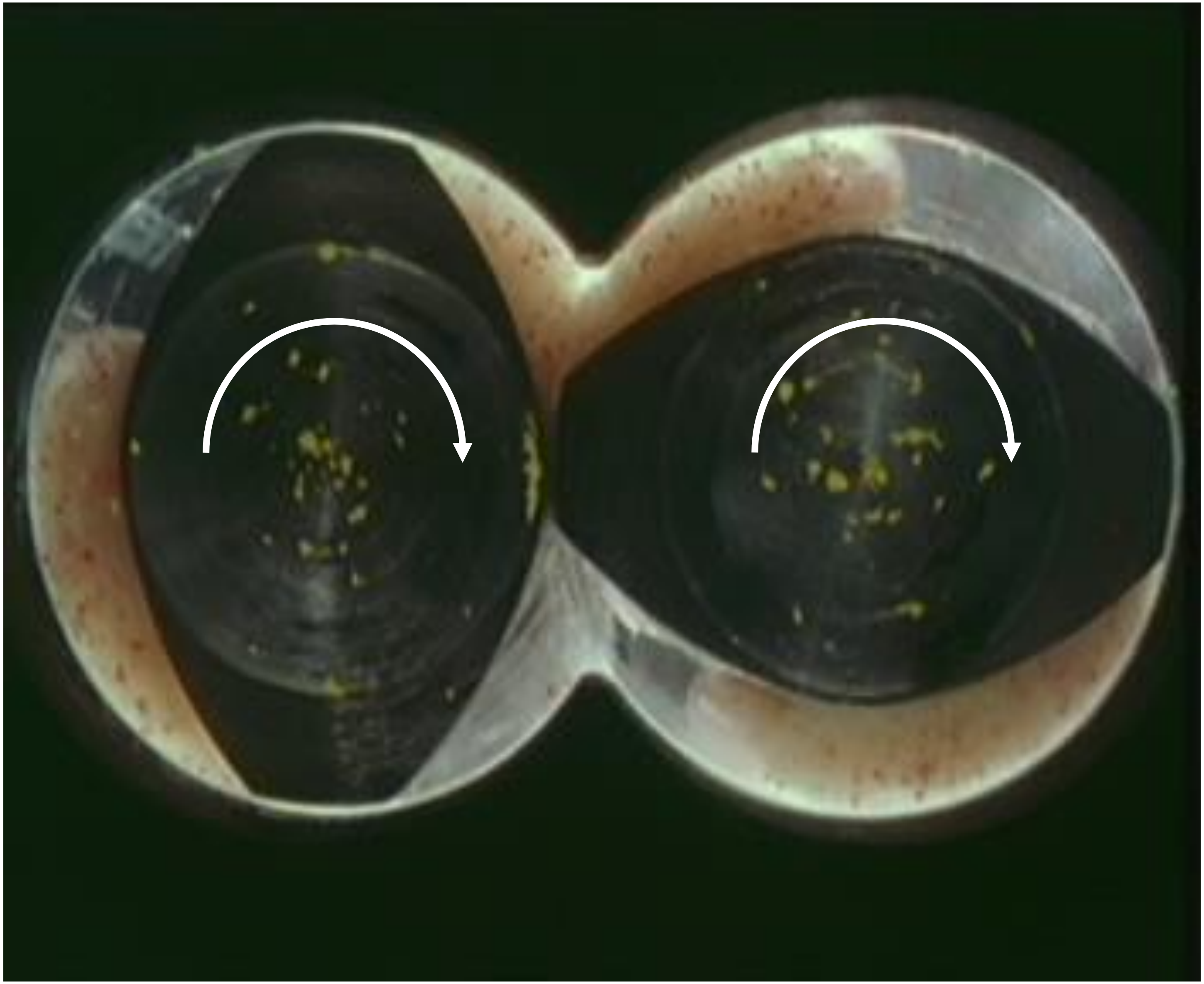
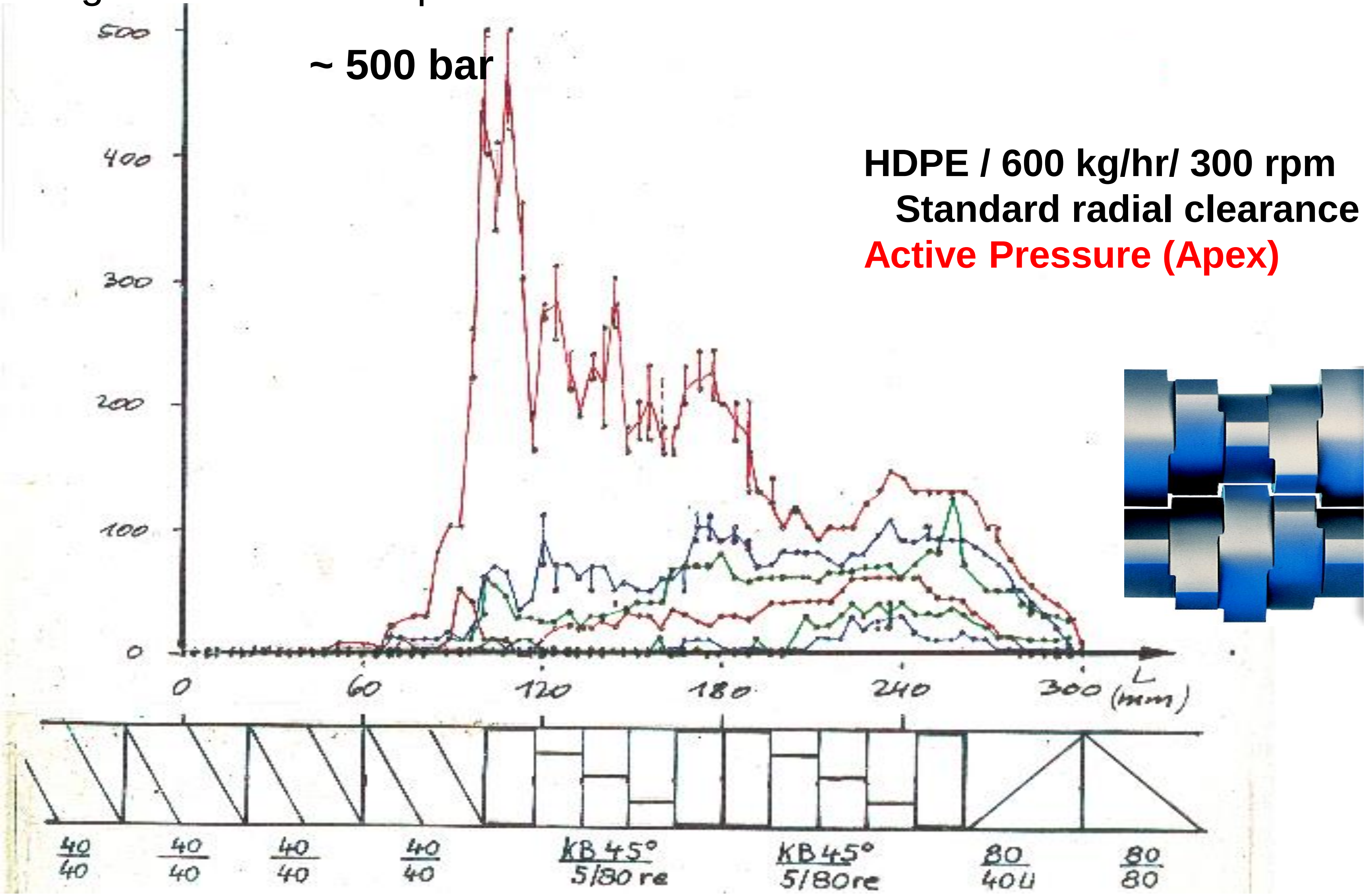


Video

Melting Zone: Pressure profile – Wide Disc KB



HDPE / 600 kg/hr/ 300 rpm

Standard radial clearance

Active Pressure (Apex)

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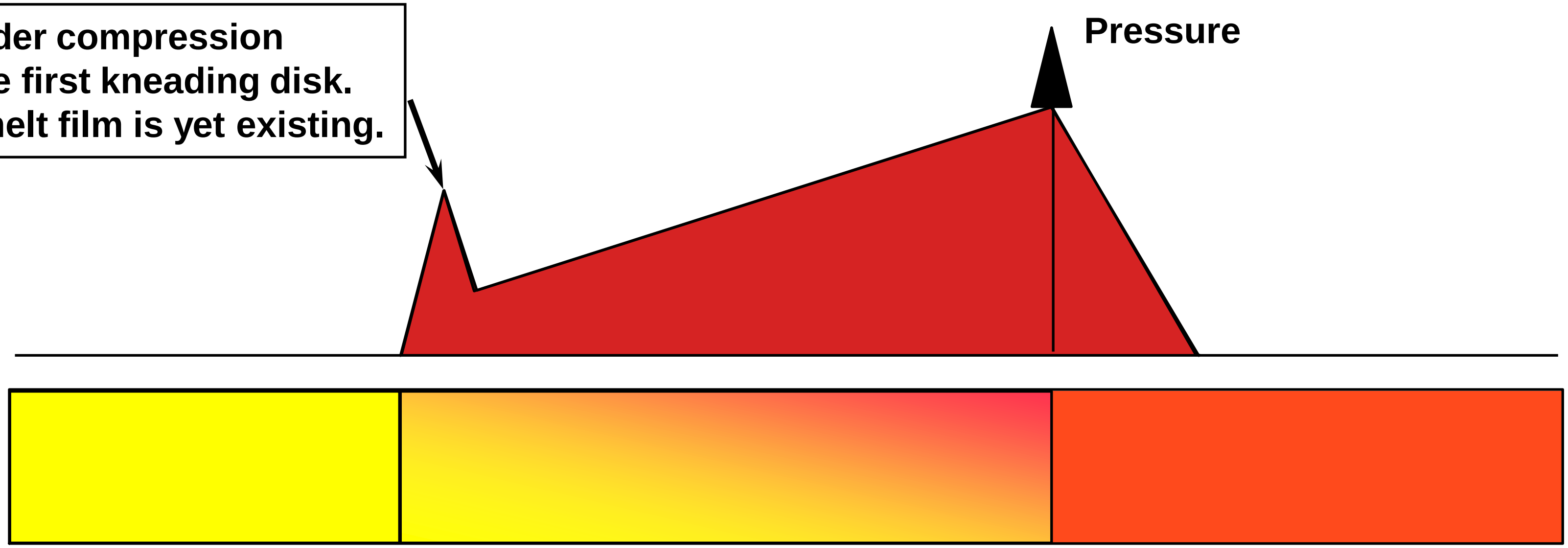
Idealized Layout of the Melting Zone

Powder compression
In the first kneading disk.
No melt film is yet existing.



Conveying of powder / pellets | **Kneading and mixing zone** | **Pressure zone** | **Conveying of melt**

Without any compression of powder or pellets, no uncontrolled premelting of the product in the conveying elements possible.

The polymer is completely molten. The screw is only partly filled.

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Solid to Melt Transition:

Impact of Stress Transfer

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Solid to Melt Transition:

Single Screw Data Analysis

Leads to New Melting Mechanism Hypothesis

Melting Slices from Tadmor and Kline

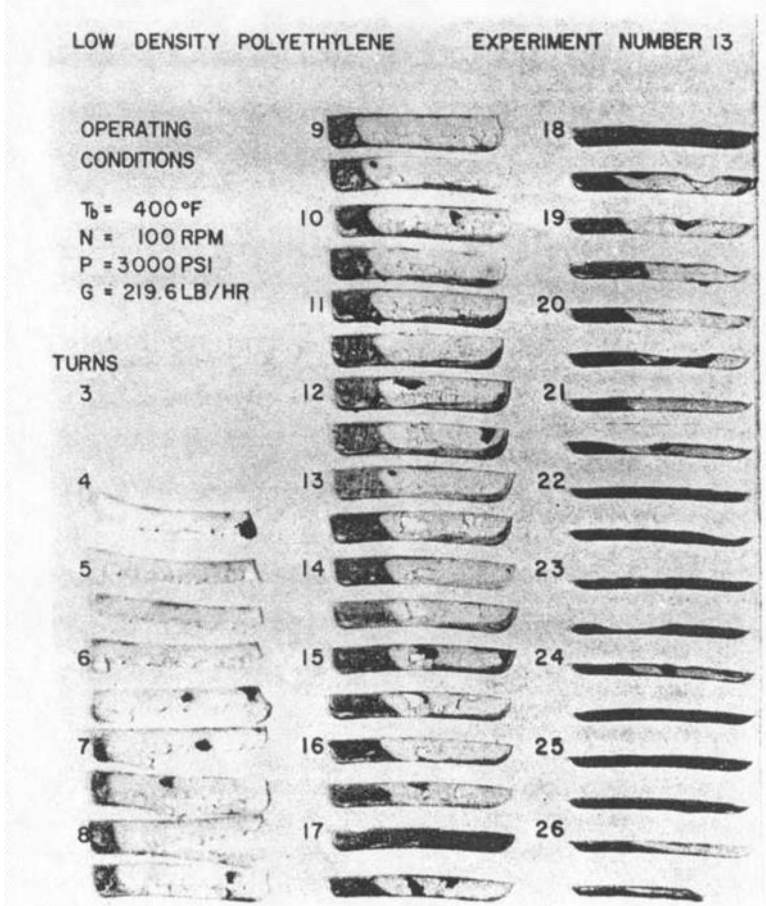

Figure 5.15 Cross sections obtained from cooling experiments. For additional information, see Tables 5.1 to 5.4.

Engineering Principles of Plasticating Extrusion, Tadmor and Klein, Krieger 1970

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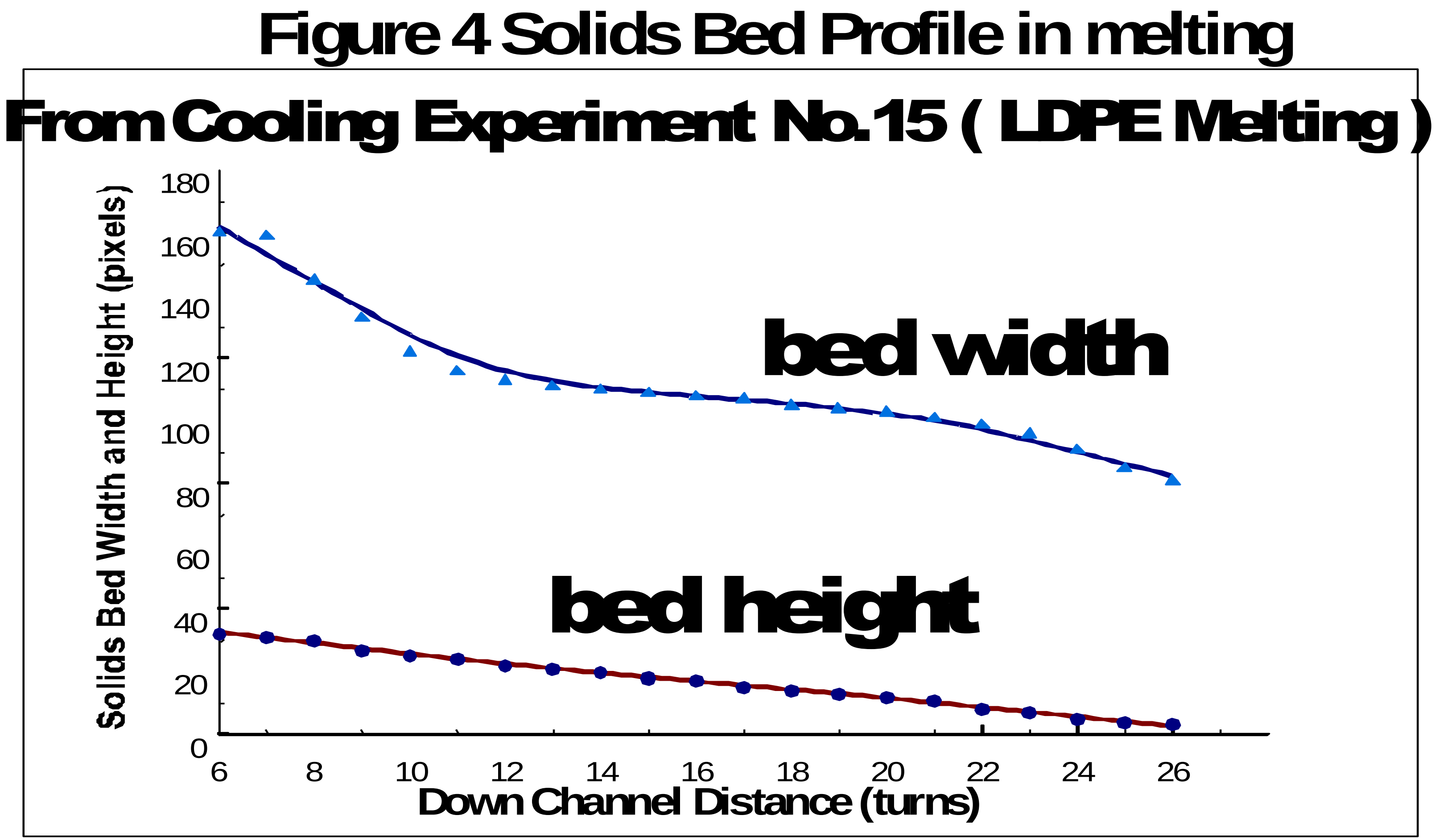
Quantitative Video Pixel Analysis of Bed Geometry Change



SOLID BED MELTING IN SINGLE SCREW EXTRUDERS
-AN ALTERNATIVE FIRST ORDER MECHANISM
-G. Campbell and Z. Tang ANTEC Paper 2004

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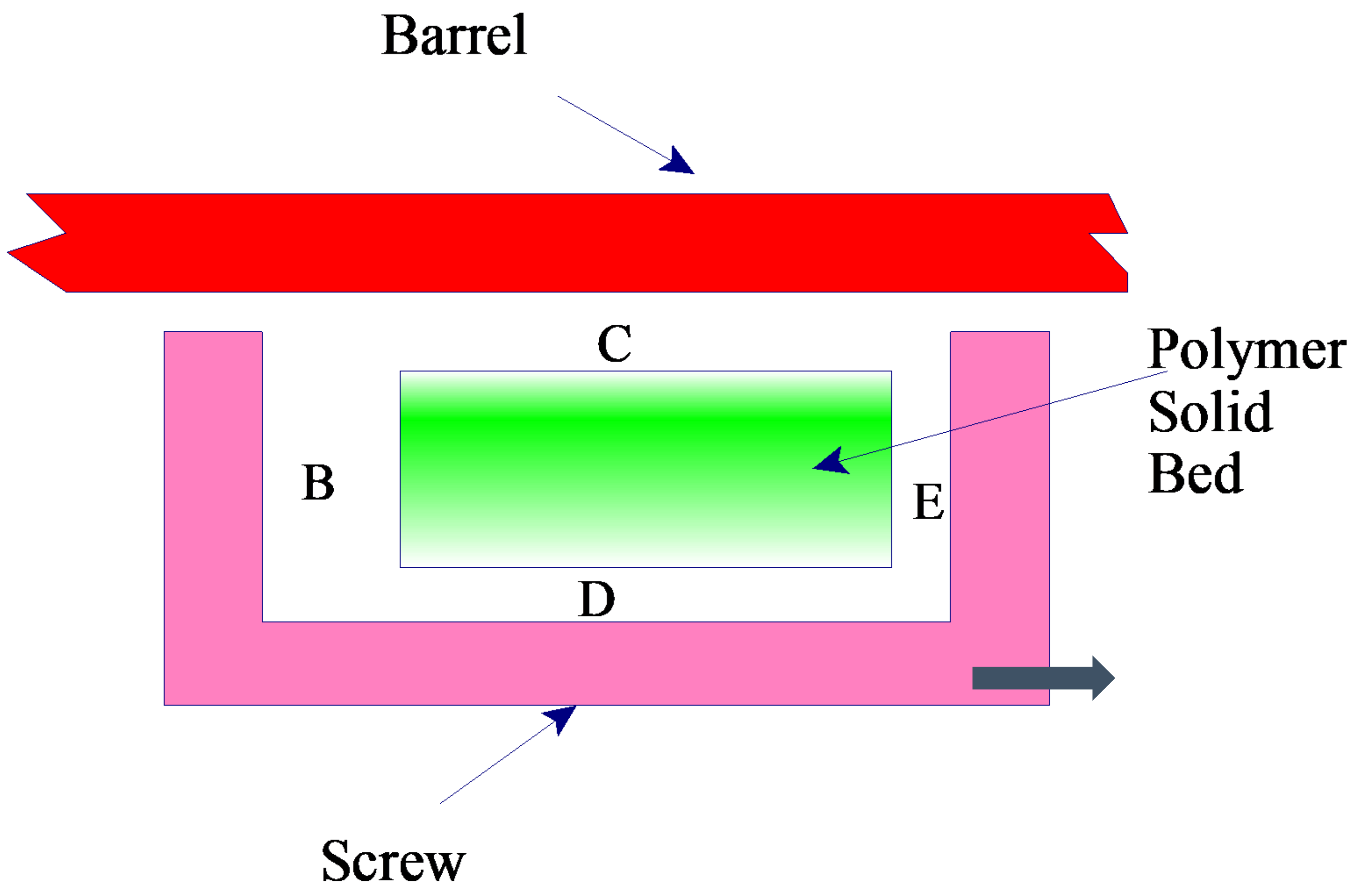
Single Screw: Four Melting Zones Around Solid Bed



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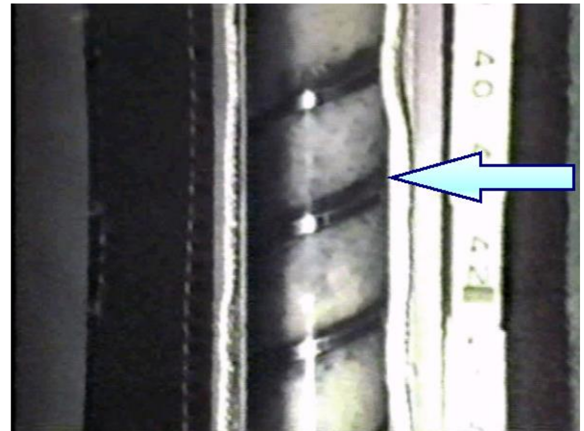
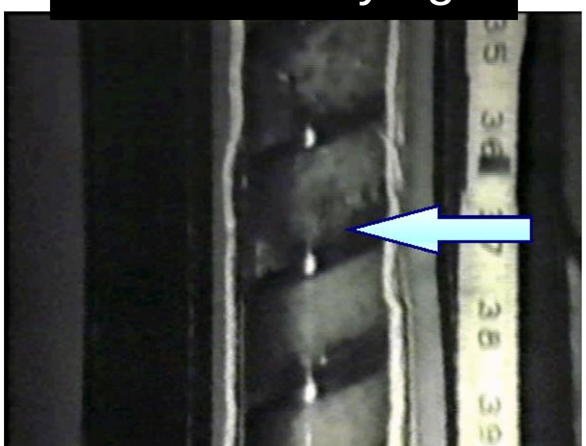
Melting Sequence Glass Barrel Extruder
Stills from Video of Polyester melting

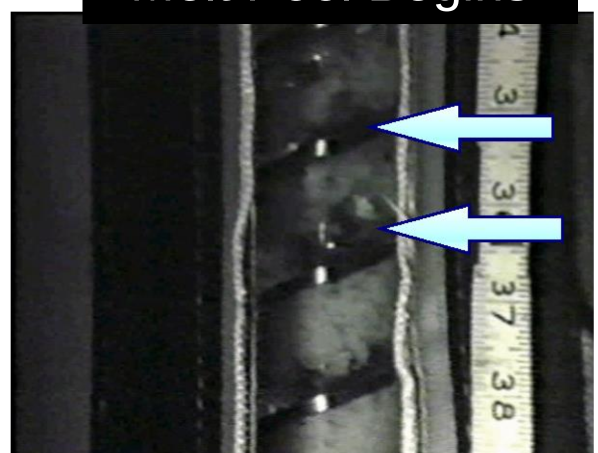
Solid Conveying



Melt Pool Begins



Full Melt Pool



Thin Y Solid Layer and Break Up

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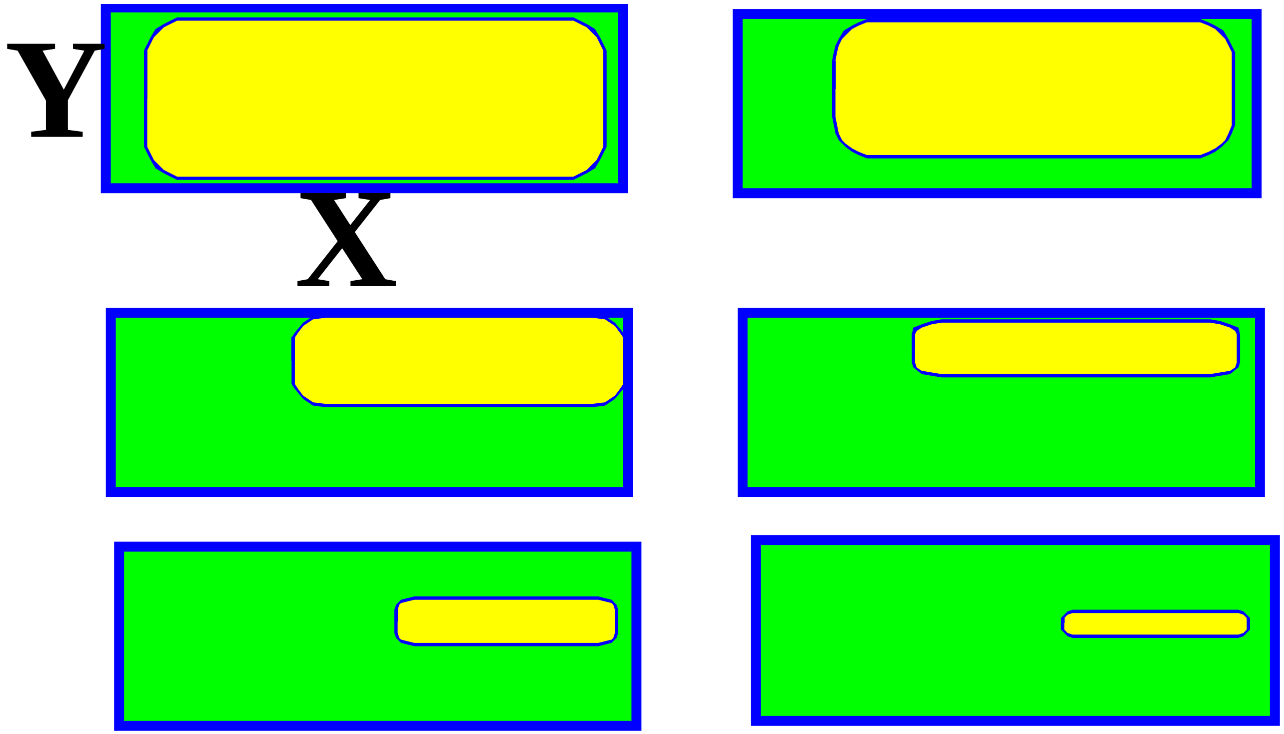
Qualitative New Melting Model



$$dY/dt \sim dQ_{barrel} + dQ_{screw\text{-}pool}$$

$$dX/dt \sim dQ_{flight} + dQ_{melt\text{-}pool}$$

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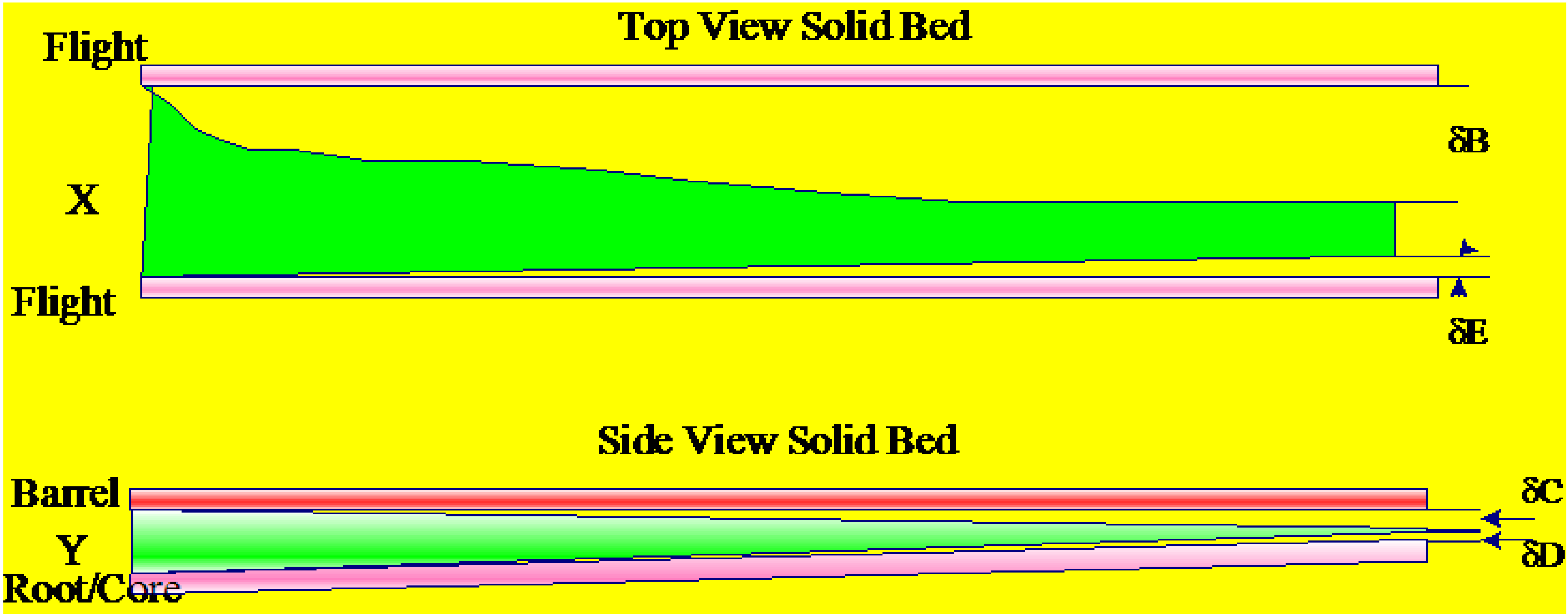
Qualitative Simulation Results



Solid Bed Goes to Zero Thickness
when Viewed from Side

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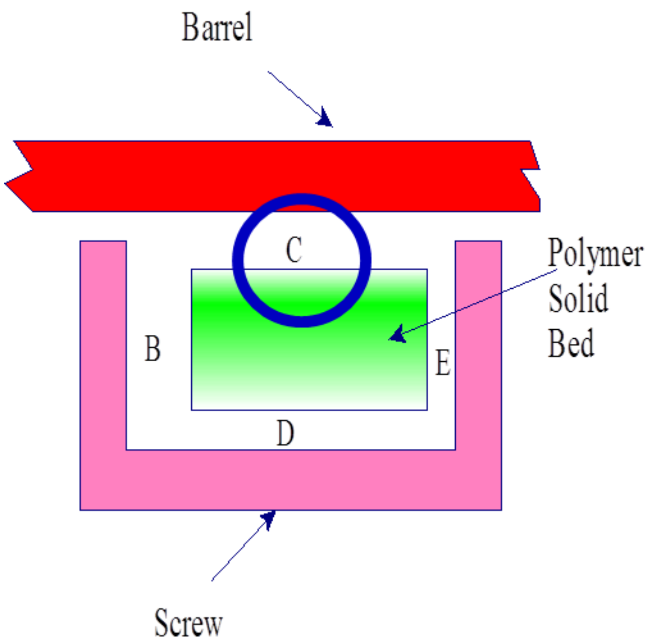
Melting Dissipation/Heat Transfer Zones



$$\delta_c = \left\{ \frac{\left[\left[2k_m\left(T_b - T_m\right) + \mu V_{\delta c}^2\right] X / \alpha\right]}{\left|\vec{V}_{sx}\right|_{\delta_c} \rho_m \left[c_s\left(T_m - T_s\right) + \lambda\right]} \right\}^{\frac{1}{2}}$$

$$V_{\delta c} = \left(Vscrewx^2 + Vsolidz^2\right)^{1/2}$$

$$\frac{dy_c}{dt_s} = -\frac{\left[\frac{k_m}{\delta_c}\left(T_b - T_m\right) + \frac{\mu V_j^2}{2\delta_c}\right]}{\rho_s \lambda + \left[\rho_s c_s \left(T_m - T_s\right)\right]}$$

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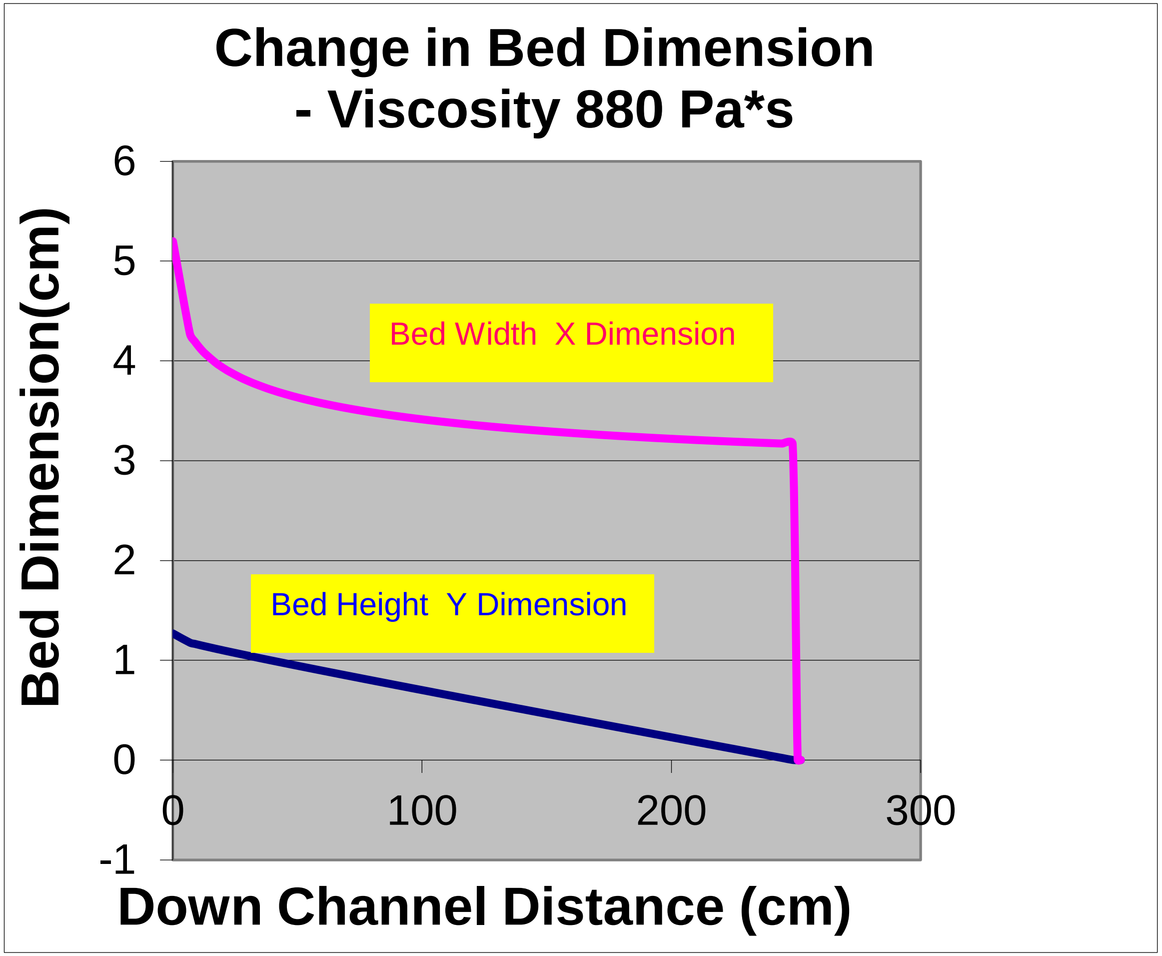
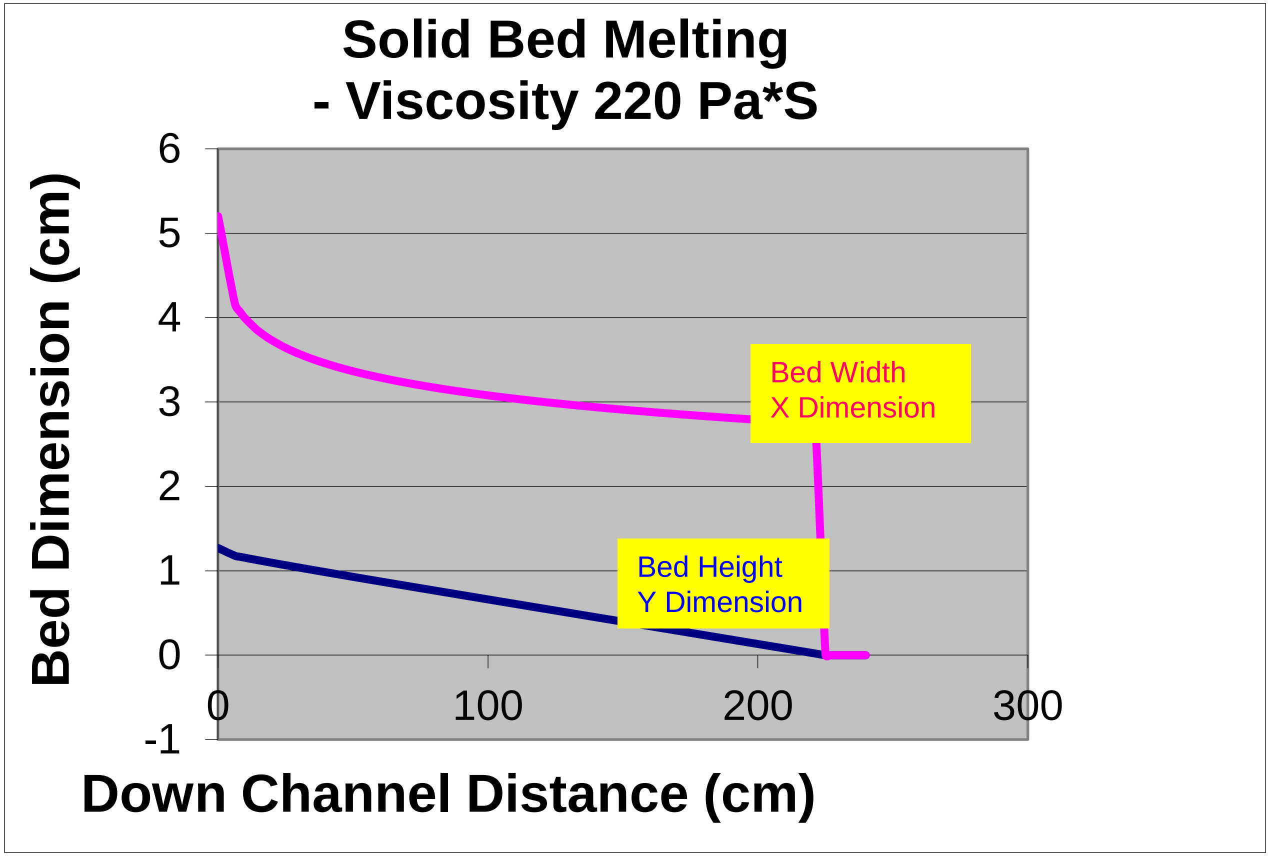
Quantitative Results Viscosity 880 Pa*S

- Bed Height 0.0 at 250 cm down channel
- Only about 50% melting in W dimension



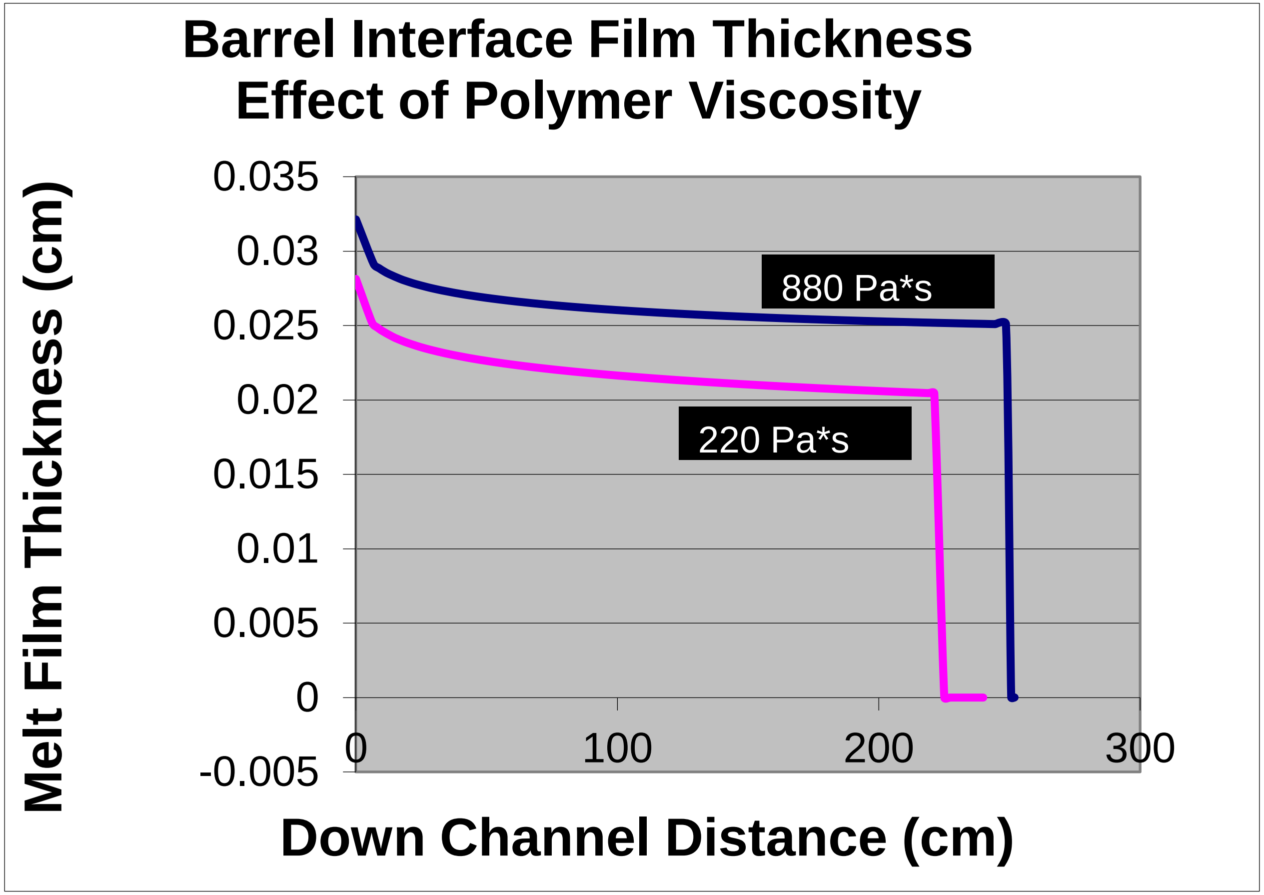
Quantitative Results Viscosity 220 Pa*S

- Bed Height 0.0 at 225 cm down channel
- Only about 50% melting in W dimension



Melt Film Thickness as Function of Viscosity

- Higher Viscosity Results in 25% Thicker Film
- Thinner Film Results in More Rapid Melting



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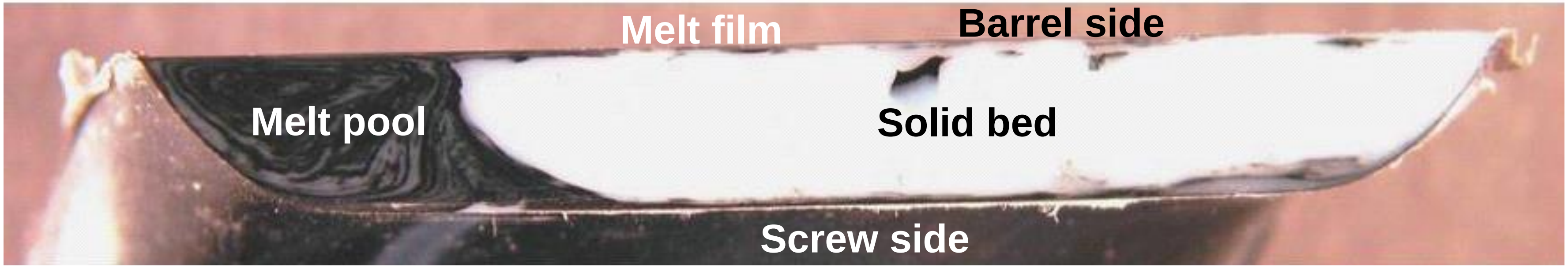
Location of Dissipation for New and Classical Melting

- New Analysis
  Melting length
  240 cm
- Historic Melting
  Length 279 cm
- Melting Length
  New Analysis
  16 % less

Model Parameter	New Analysis	Historical Analysis
Vectorial Velocity ,δC, cm/s	8.7	29.5
Vectorial velocity ,δD, cm/s	20.3	2.4
Melting energy zone C, J/s	1140	1980
Melting energy zone E, J/s	480	0
Melting energy zone D, J/s	340	0
Melting energy zone B, J/s	20	0
Total melting energy, J/s	1980	1980

Summary: Single Screw Melting Process



- Melting occurs due to viscous energy dissipation in the melt films between the solid bed and the screw and barrel surfaces.
- Primary mixing occurs during the melting process.
- Melting progresses down the length of the transition section (melting section). About 80 % of the resin is melted at the barrel surface and the remaining 20 % at the screw root.
- At the barrel surface, the motion of the screw forces the new molten resin into Melt Pool
- At the screw surface, a pressure gradient exists that forces newly molten resin into the melt pool

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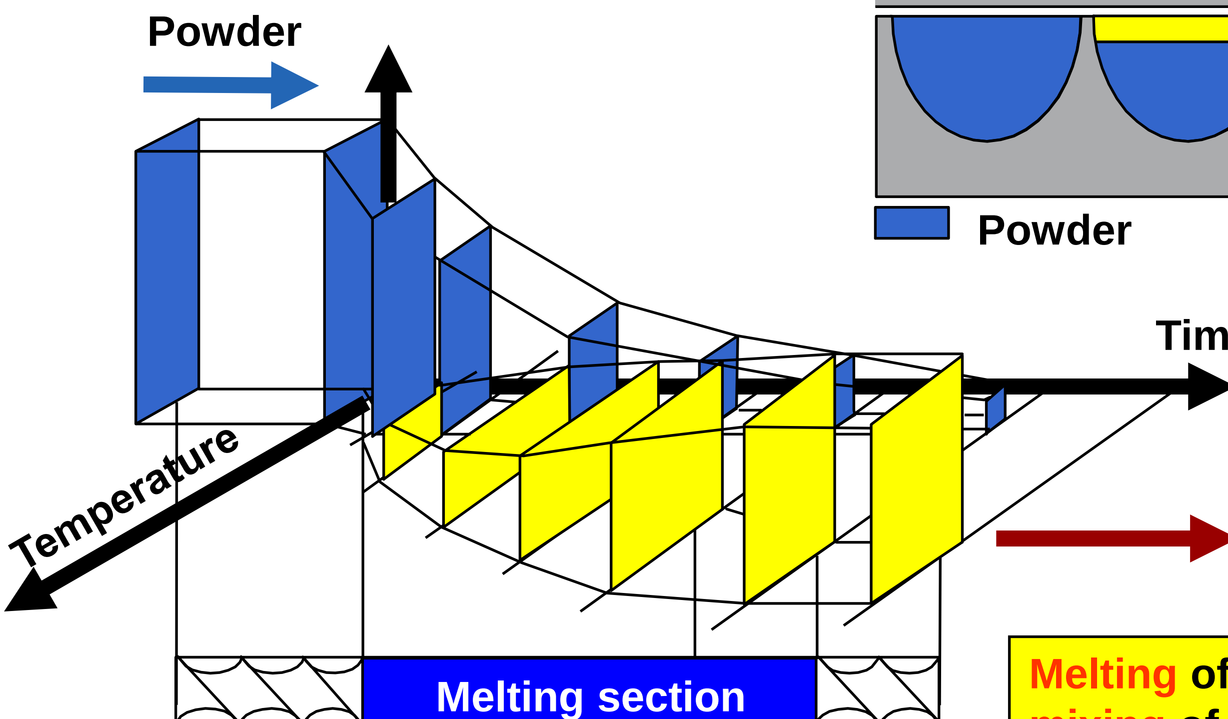
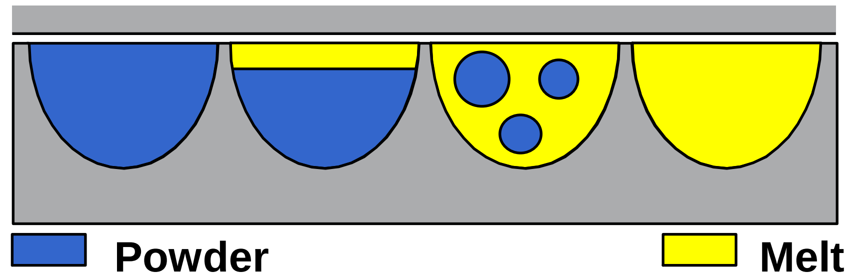
Solid to Melt Transition:

Impact of Stress Transfer

Twin-screw Kneading Block Mixing

Twin-screw Melting Progression: Thermal Homogenization – Melt Stress Transfer





Melting of the powder and immediate mixing of the melt with the remaining powder or mixing of the high and low viscous particles results in a results in a homogeneous melt.

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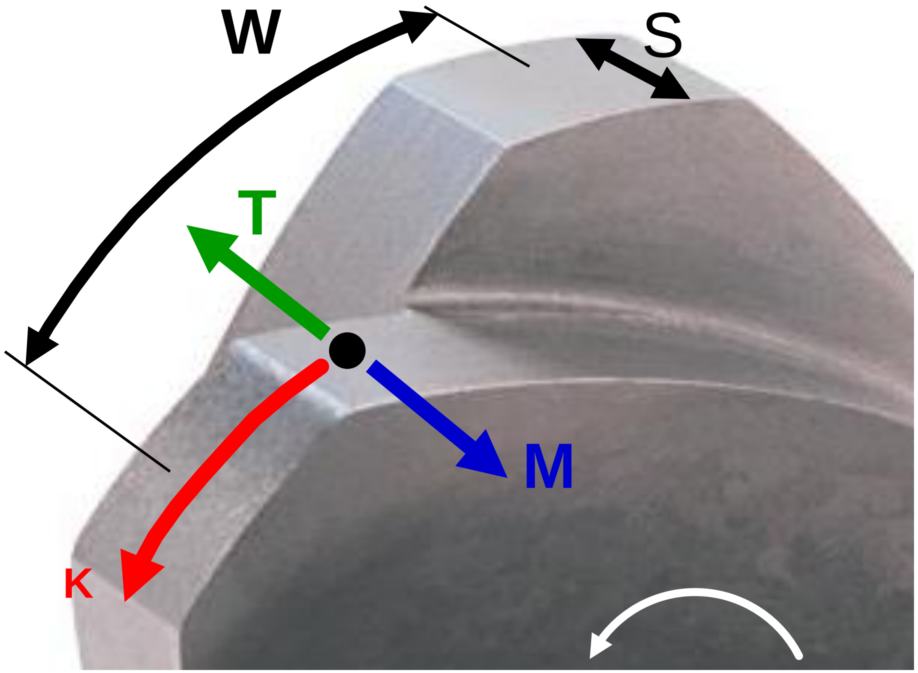
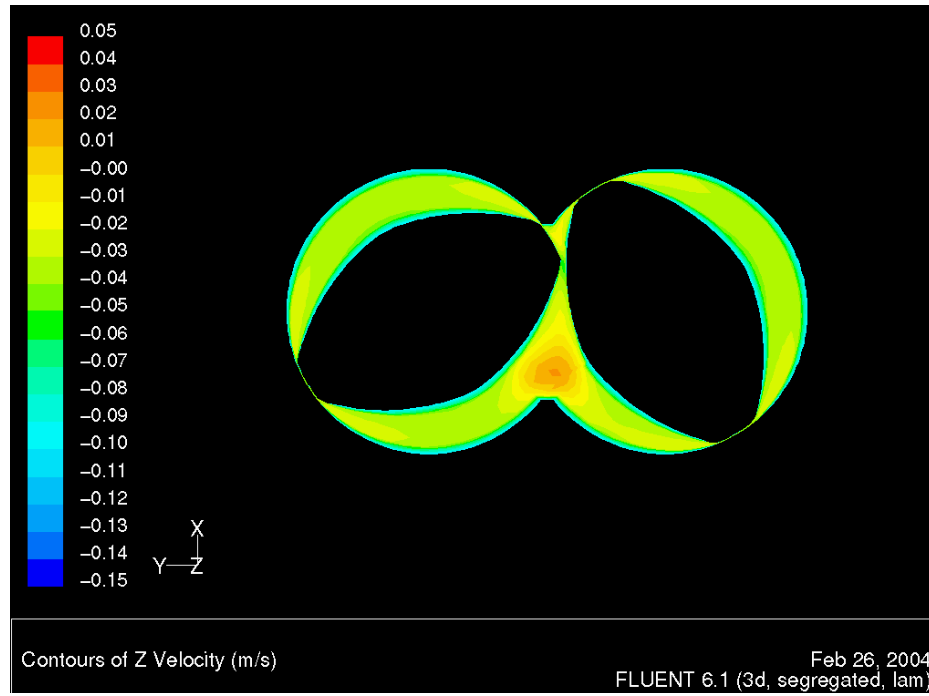
Twin-screw Melting Progression:
Kneading Elements - Melt Stress Transfer





W... Staggering angle
S ... Width of the disk
T ... Transport
M ... Distributive mixing
K ... Minimal flow in full diameter elements

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Twin-screw Melting Progression:
Thermal Homogenization – Melt Stress Transfer

Video

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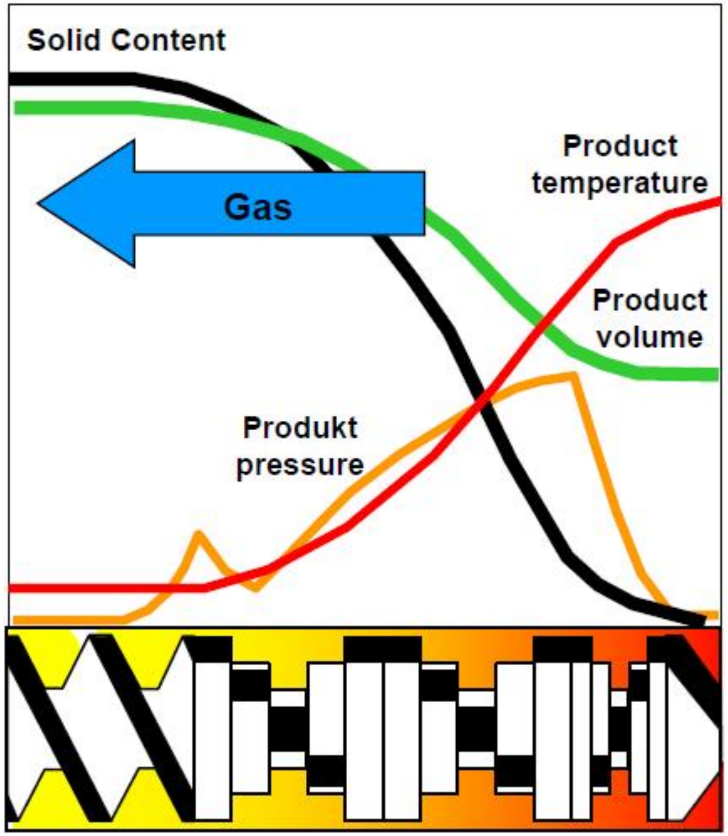
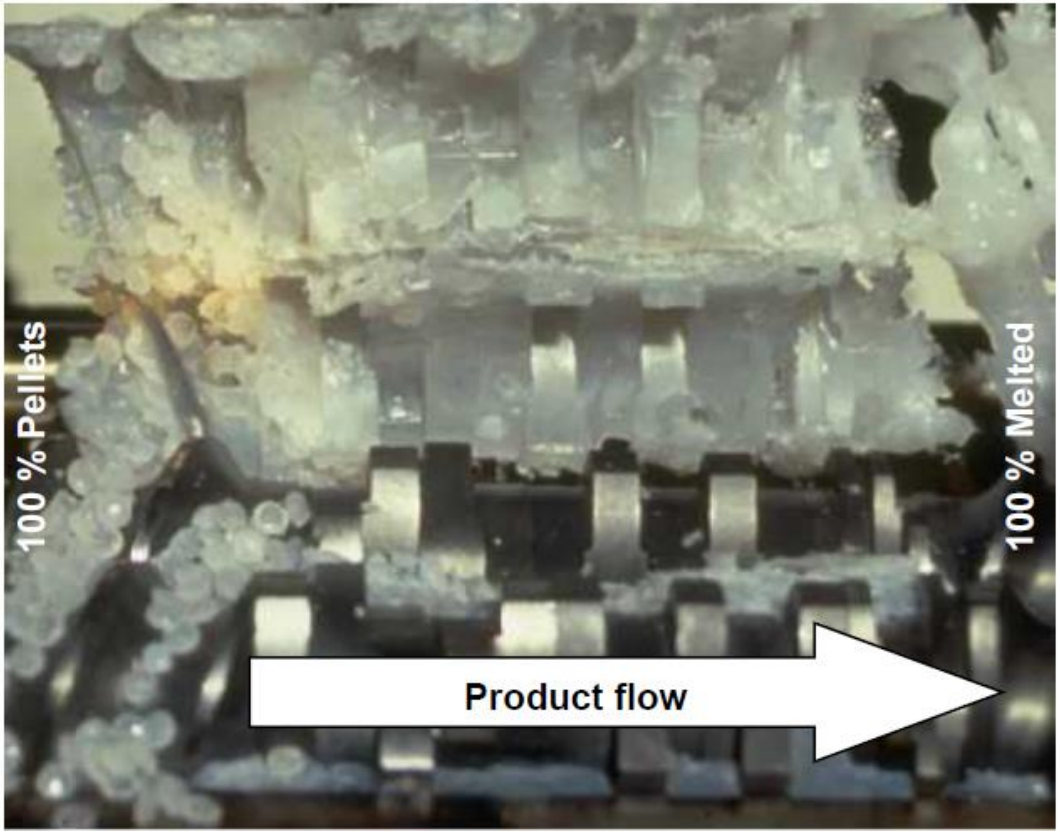
Idealized Layout of the Melting Zone





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Solid to Melt Transition:

Thermal Homogenization / Conduction Melting Residual Solids and Gels

Single Screw

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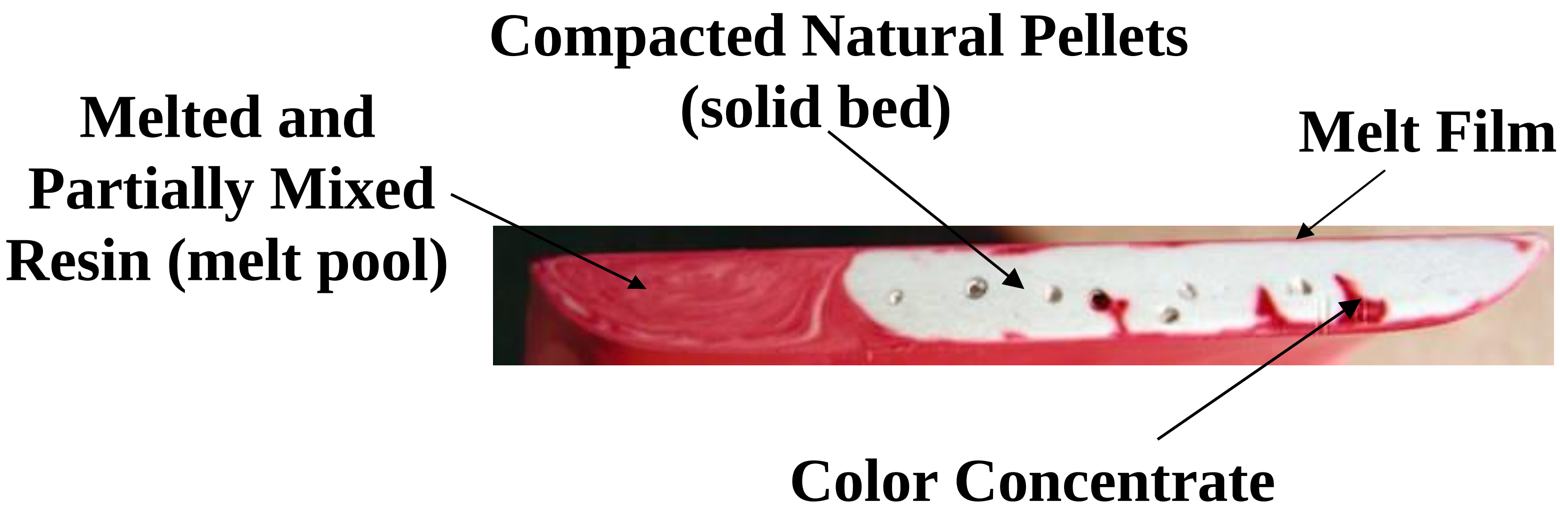
Melting of the resin: primary method for Single Screw mixing

- The best mixing occurs in the melt film between the solid bed and the barrel wall.
- The shear stress is very high in the melt film.
- **A secondary mixing section is generally needed for most applications.**



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Why is a secondary mixing required

- As a screw is rotated faster, a speed will be reached where solid resin is discharged – solid bed break-up
- Solids in the discharge can look like a poorly mixed system.
- A secondary mixer or solids trap is needed to finish the melting process.
- Increased Screw speed: Melting ~ 0.7 * Solid Pumping

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Solid Bed Breakup / Unmelt Leaving Extruder

Cross-sectional views of extrudate samples at a letdown ratio of 100 to 1 of a white pigmented ABS resin with a black color concentrate for a melting-mixing experiment.

Why Solid Bed Breakup?
Reasonable Question Given The Data Presented

- Solid Bed Gets Weak and Thin
- Shear Stress Under Bed
- Bed Breaks and Sends Unmelts Forward

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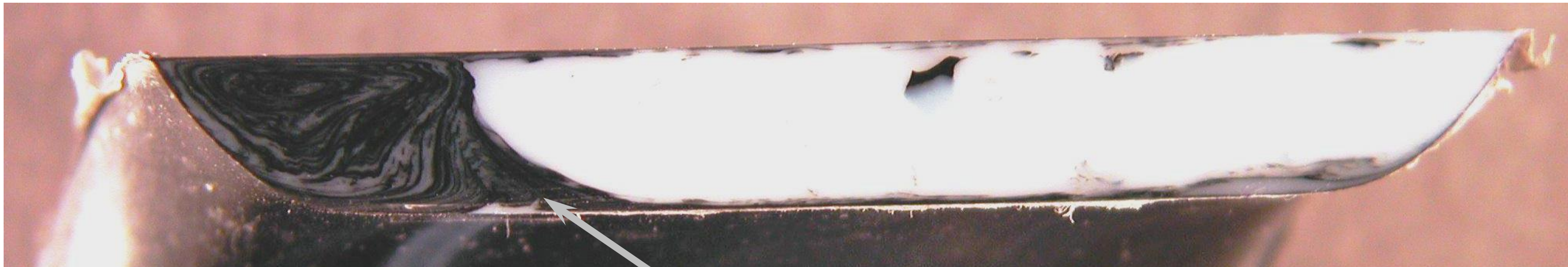
Single Screw Melt Films

Barrel side

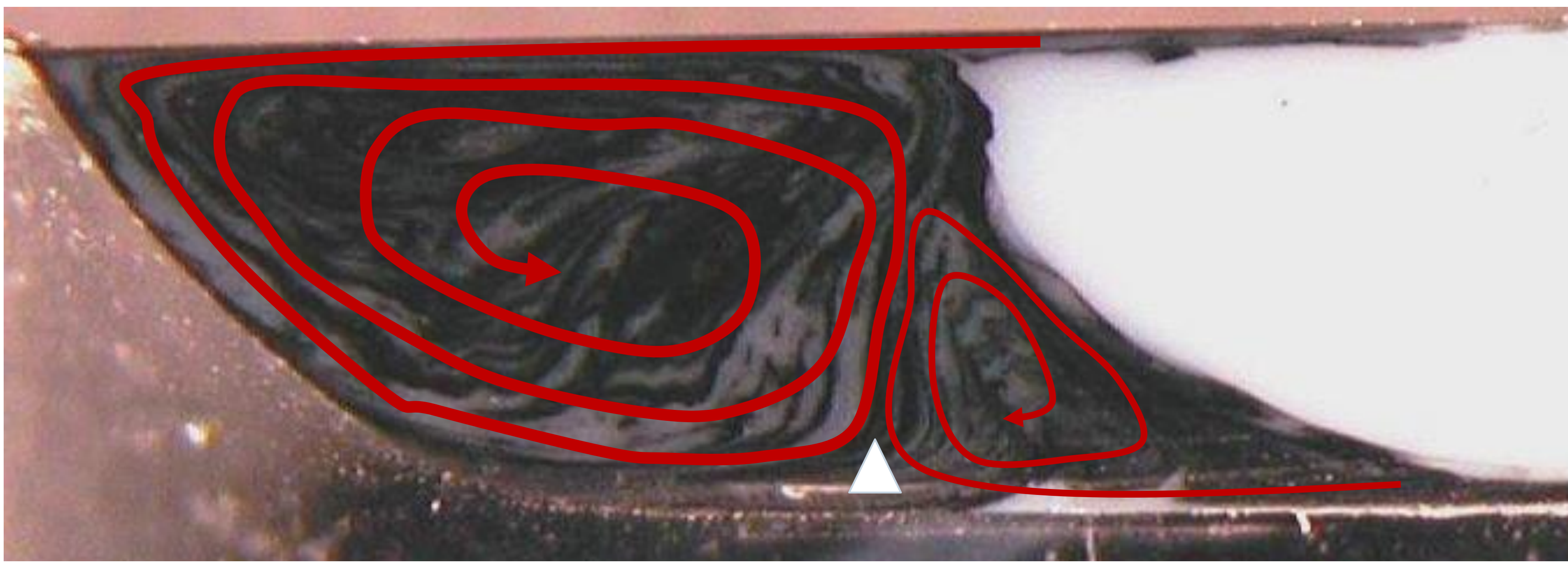
a)



Screw side

Flow from melt Film D
to the melt pool

b)



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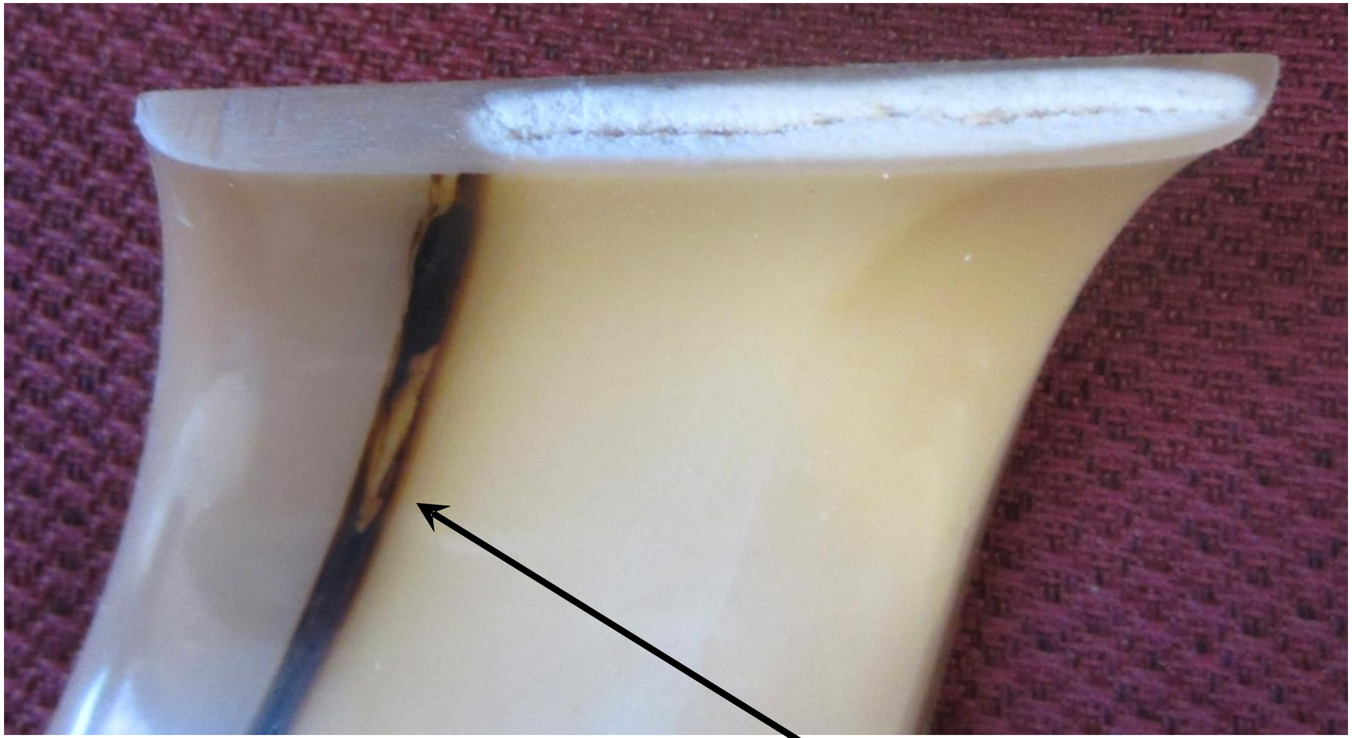
Degradation in Single Screw Due to Stagnation: Eddie Between the Flows



Degraded Resin at the Screw Root
Where the Flow Streams Merge

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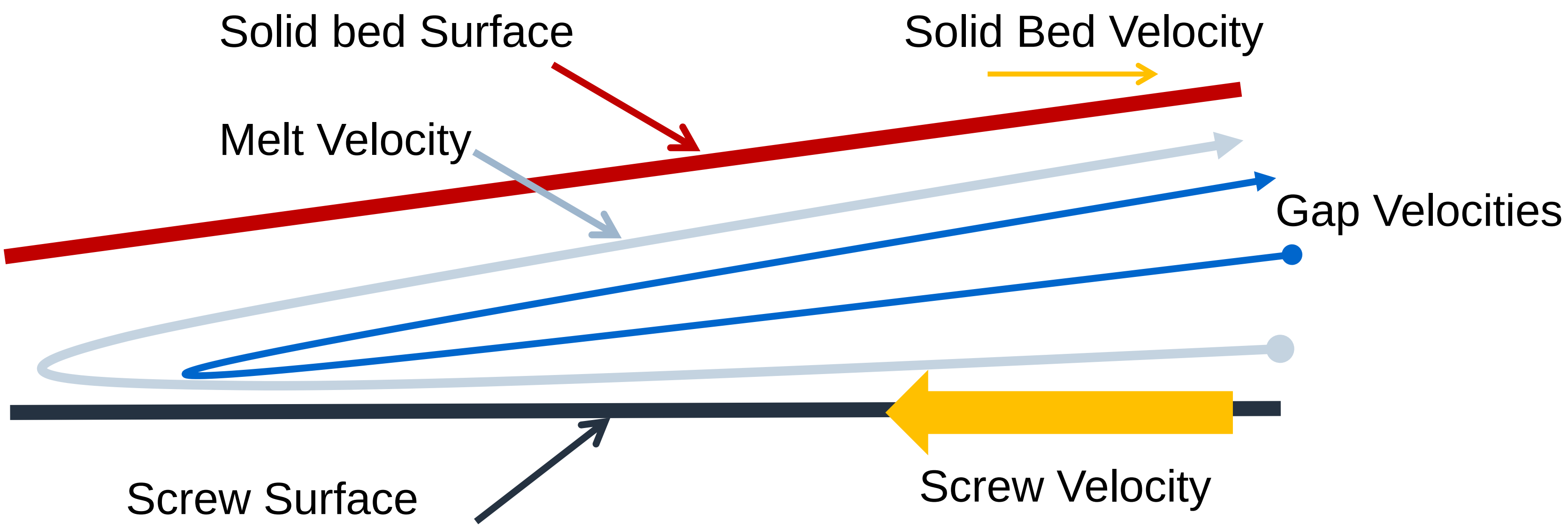
Velocity in Solid Bed:
Screw Surface in Gap Between Screw Core and Bed



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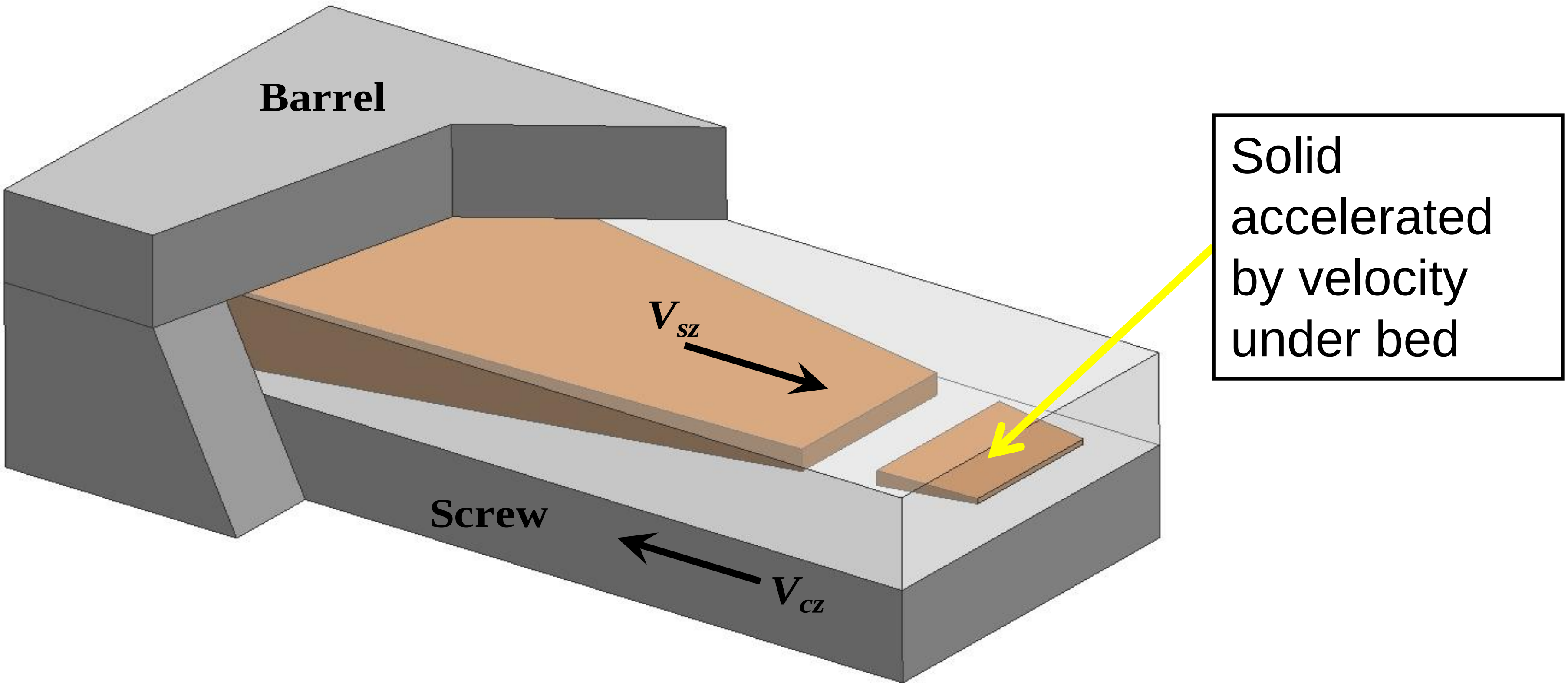
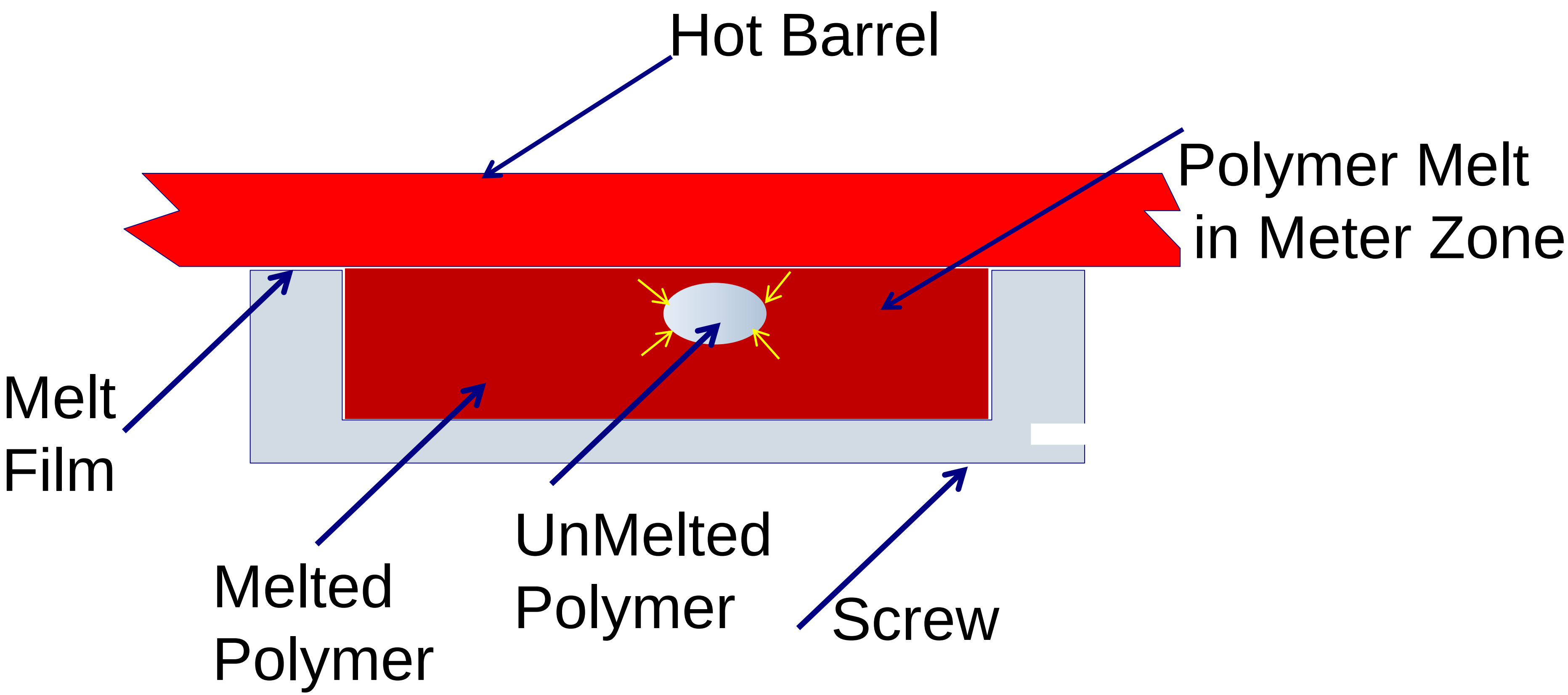
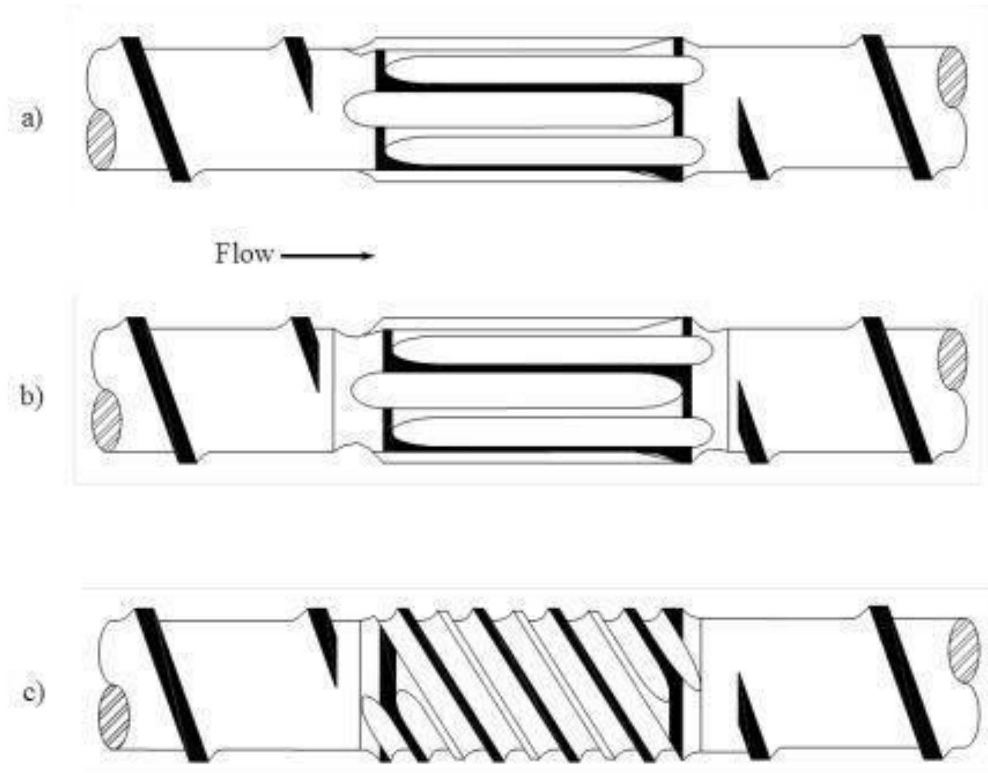
Solid Bed Breakup due to Fluid Velocity generated surface shear stress



After Bed Break-Up: Conduction Dominated Melting



Maddock Style Mixers



Schematic for Maddock-style mixers. a) a mixer with the flutes aligned in the axial direction, b) an axial mixer with a pressure relief zones at the entry and exits, and c) a mixer with spiral flutes (courtesy of Jeff A. Myers of Robert Barr, Inc.).

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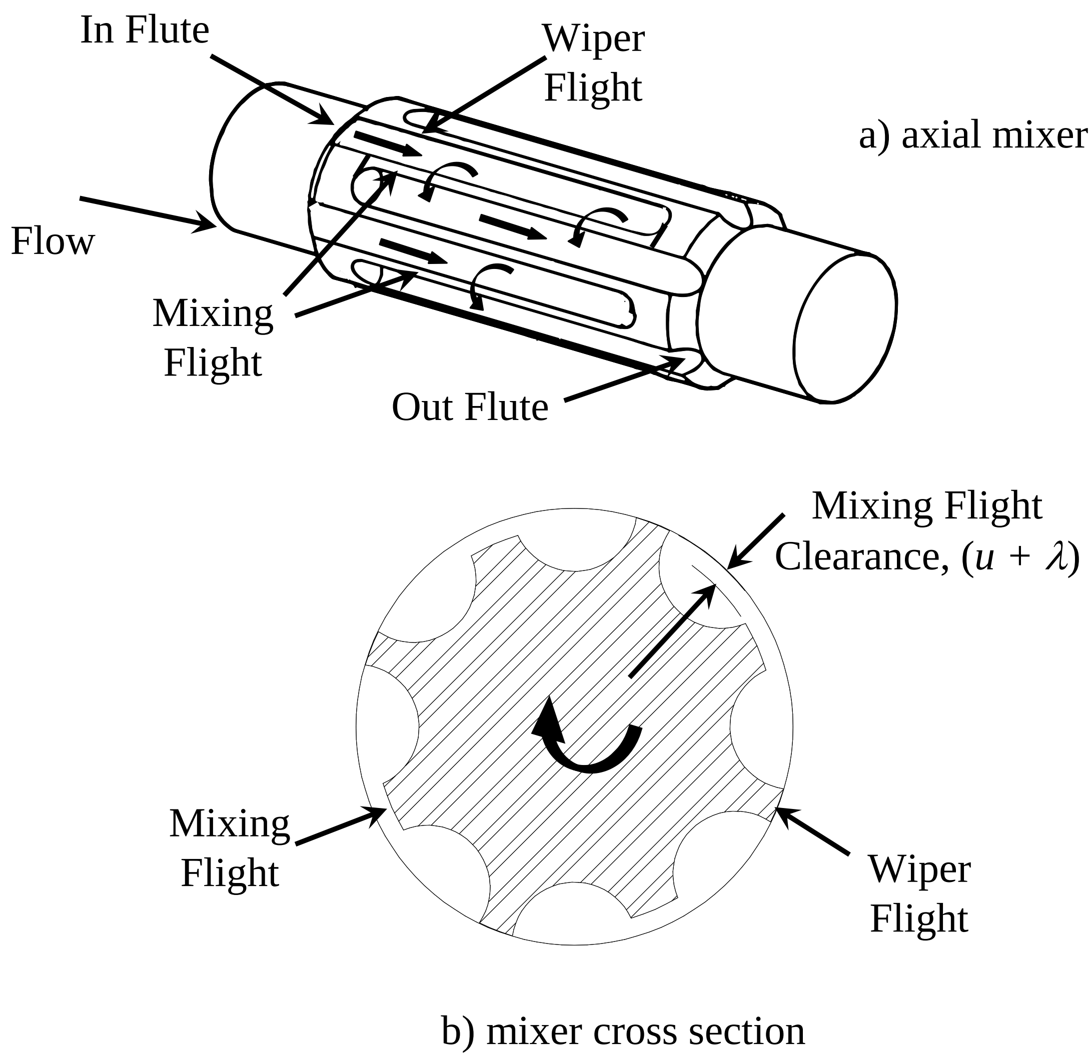
Maddock Style Mixer



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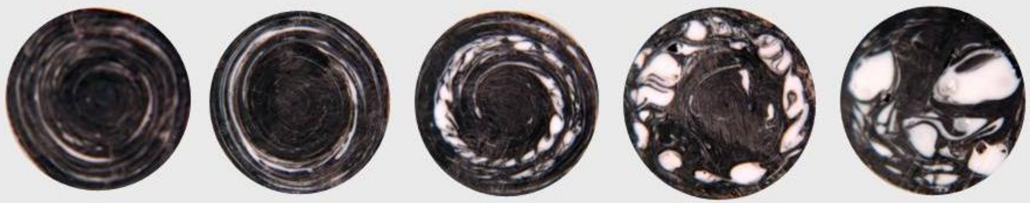
The Melting Process Can Be Improved with Enhanced Screw Designs



30 rpm 28 kg/h	60 rpm 56 kg/h	90 rpm 83 kg/h	120 rpm 109 kg/h	150 rpm 135 kg/h

Conventional single-flighted screw

Maximum rate before melting problem: 65 kg/h at 70 rpm

30 rpm 33 kg/h	60 rpm 62 kg/h	90 rpm 85 kg/h	120 rpm 110 kg/h	150 rpm 135 kg/h

Energy Transfer (ET) screw

Maximum rate before melting problem: 101 kg/h at 110 rpm

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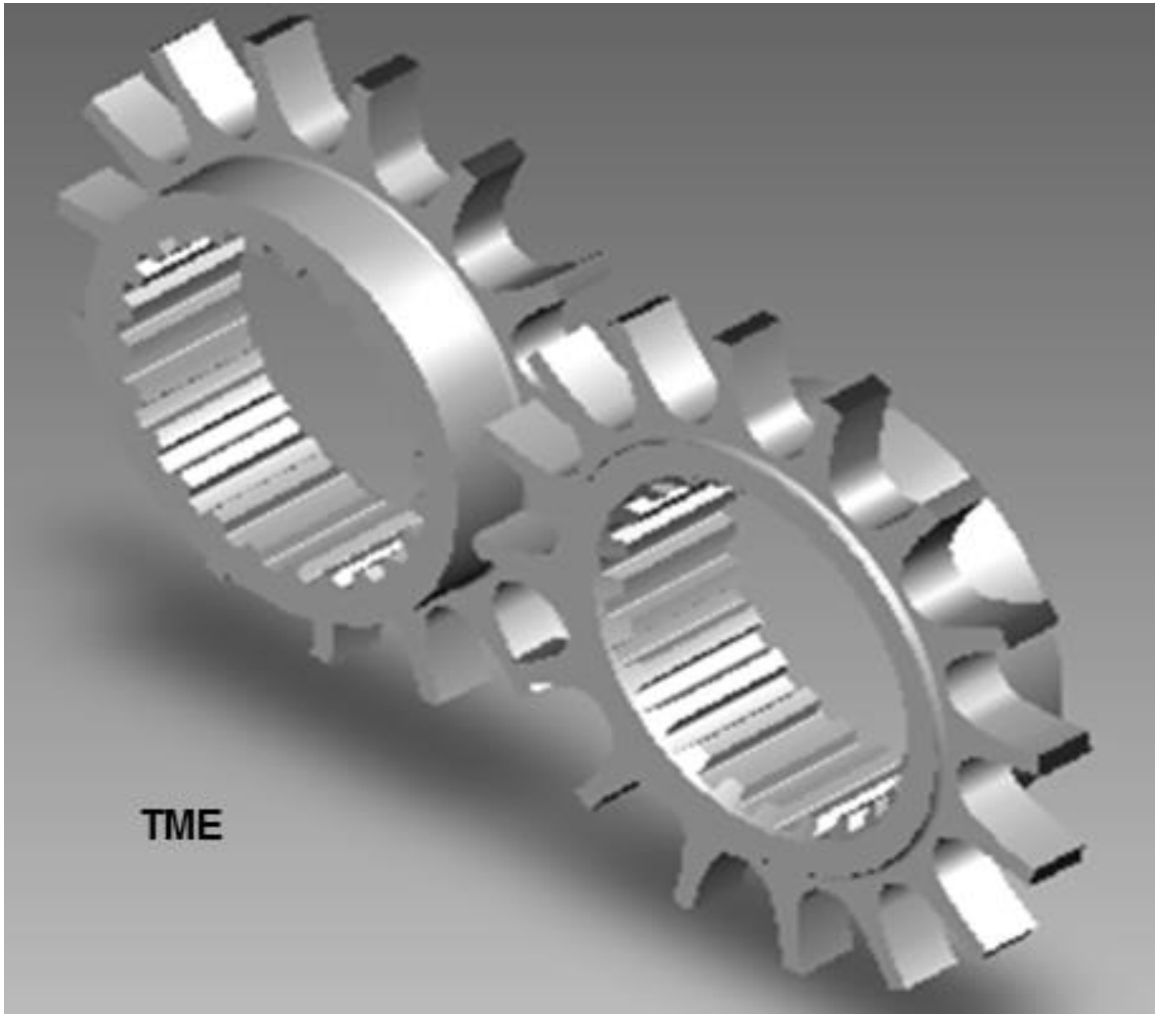
Solid to Melt Transition:

Thermal Homogenization / Conduction Melting Residual Solids and Gels

Twin-Screw

Twin-screw Melting Progression: Thermal Homogenization – Low Viscosity Melt



Video

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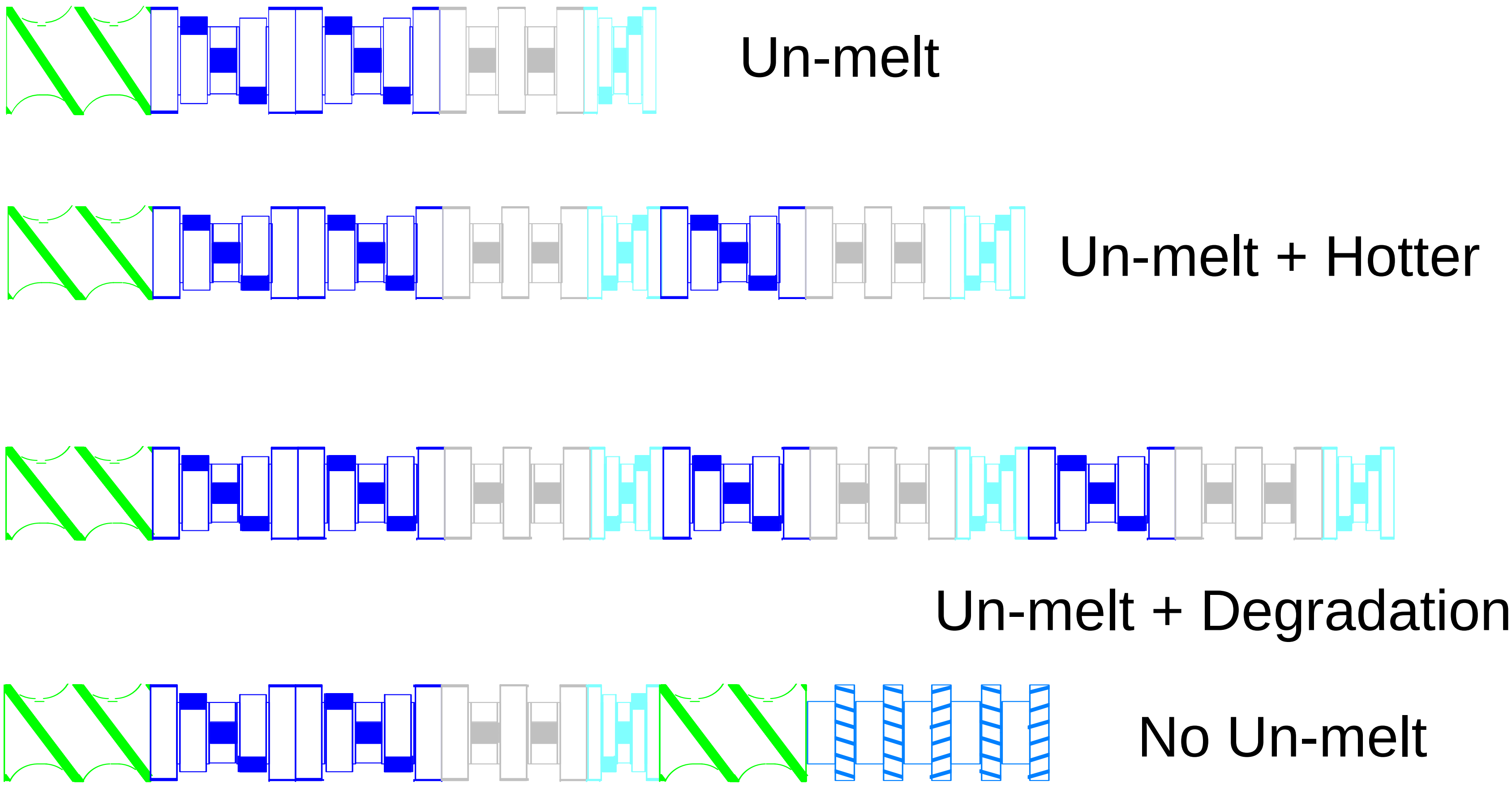
Twin-screw Melting Progression:
Thermal Homogenization – Low Viscosity Melt



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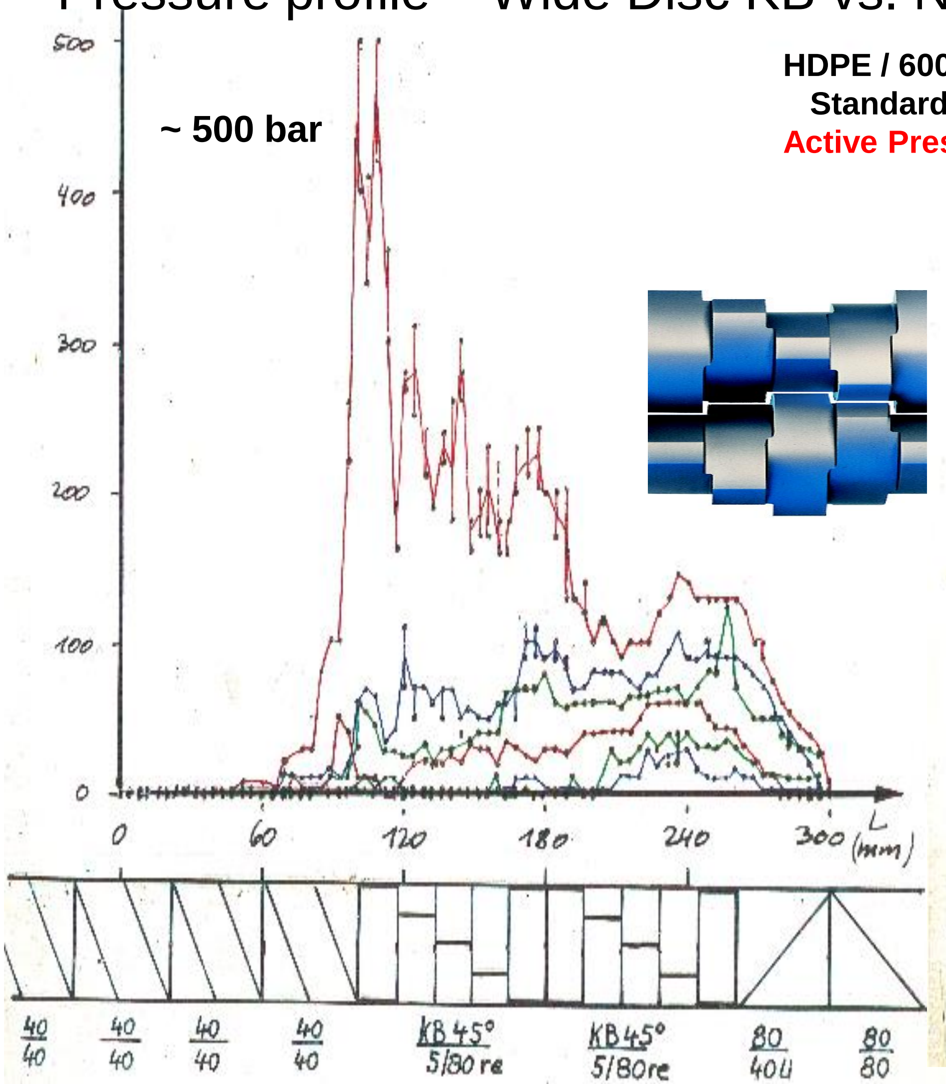
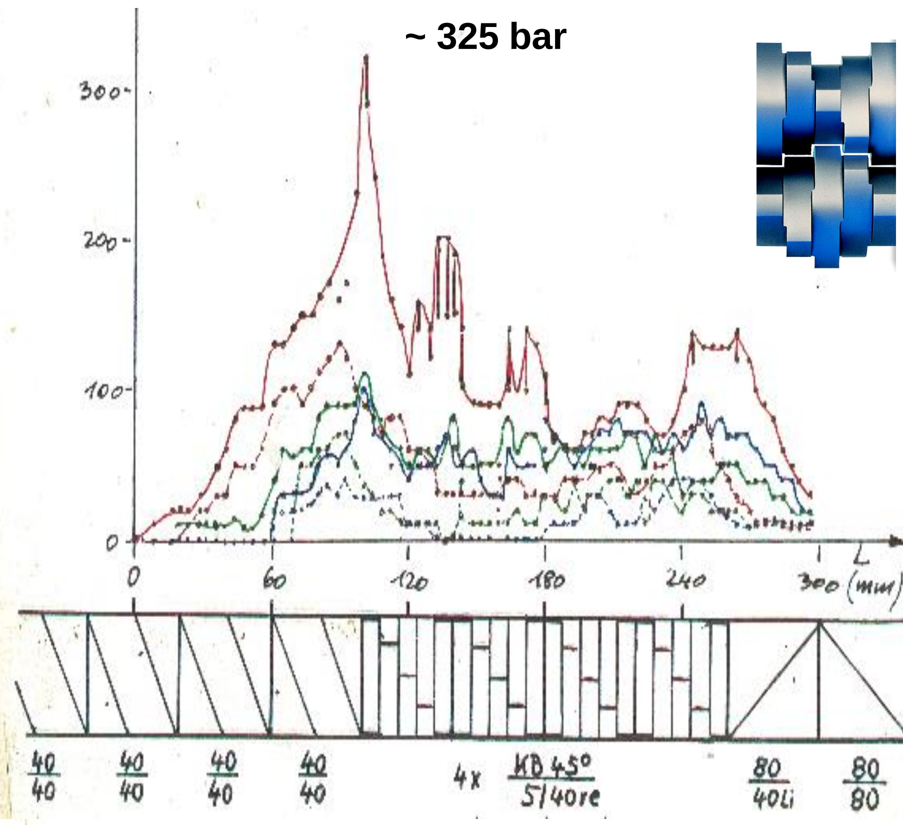
Melting Mechanisms: Single vs. Co-rotating Twin-screw Extruders

- Twin-screw compounding system overview
- Single Screw Melting Analysis
- Melting Mechanisms in the Twin-screw Compounder
  - External Thermal Energy Transfer
  - Frictional Heat Build-up / Energy Transfer
  - Mechanical Deformation
  - Melt Stress Transfer
  - Thermal Homogenization
- Influential Variables
  - Machine Design – i.e. screw configuration
  - Process Conditions – Temperature, rpm, rate/rpm
  - Material Characteristics – particle size, Tm, Melt viscosity
- Summary

Melting Mechanisms: Impact of Screw Configuration
Pressure profile – Wide Disc KB vs. Narrow Disc KB

HDPE / 600 kg/hr/ 300 rpm
Standard radial clearance
Active Pressure (Apex)





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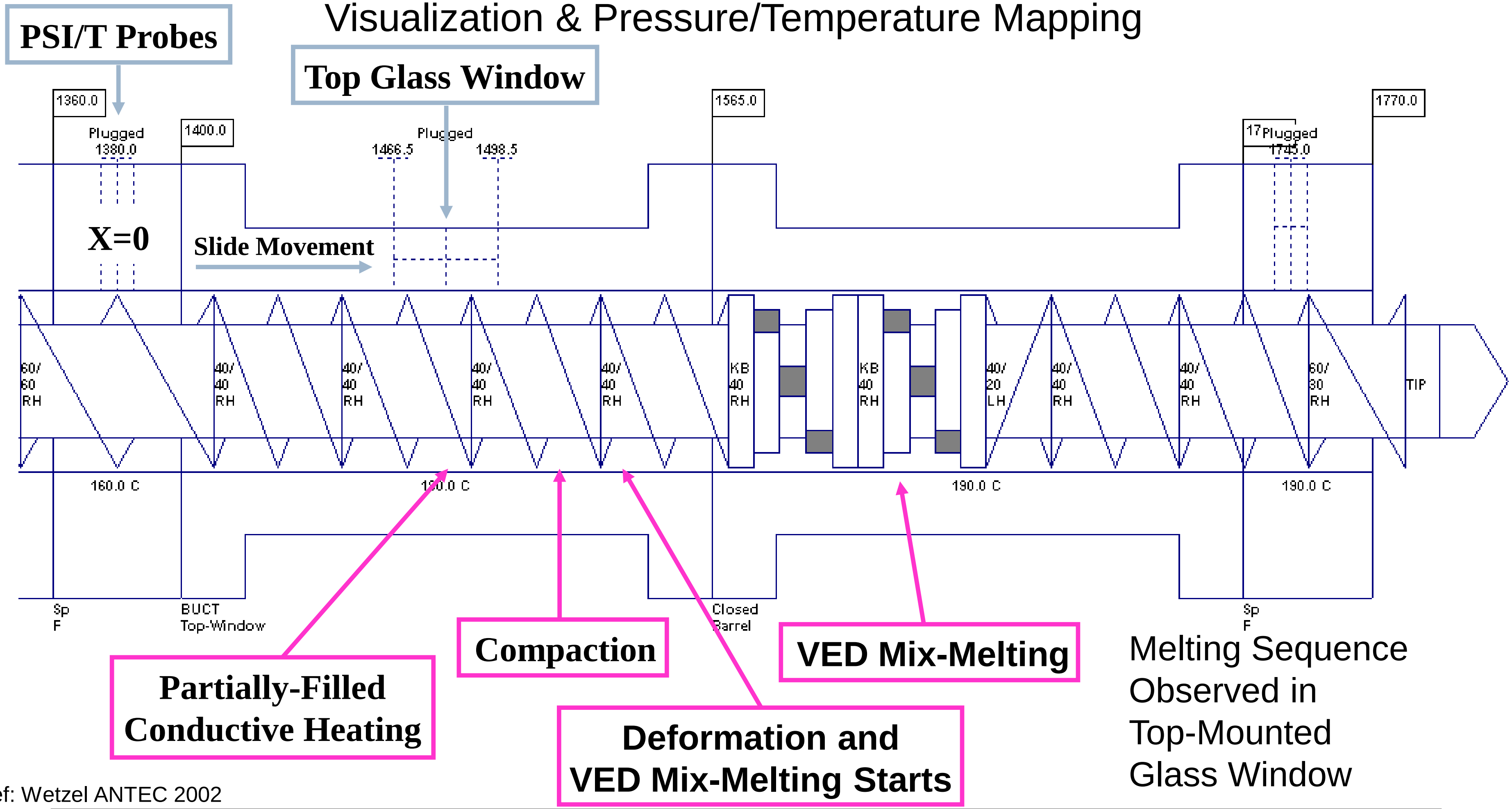
Melting Mechanisms: Impact of Process Conditions
DuPont ZSK 40mm EZ-Slide LDPE Pellet Melting Study

Visualization & Pressure/Temperature Mapping



Melting Sequence
Observed in
Top-Mounted
Glass Window

Ref: Wetzel ANTEC 2002

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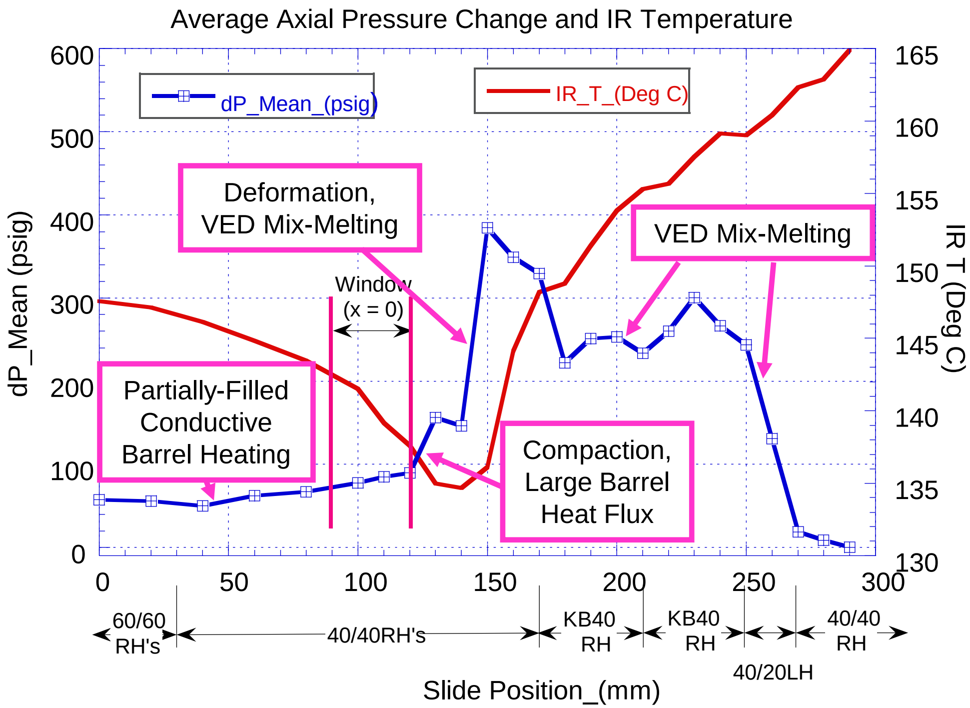
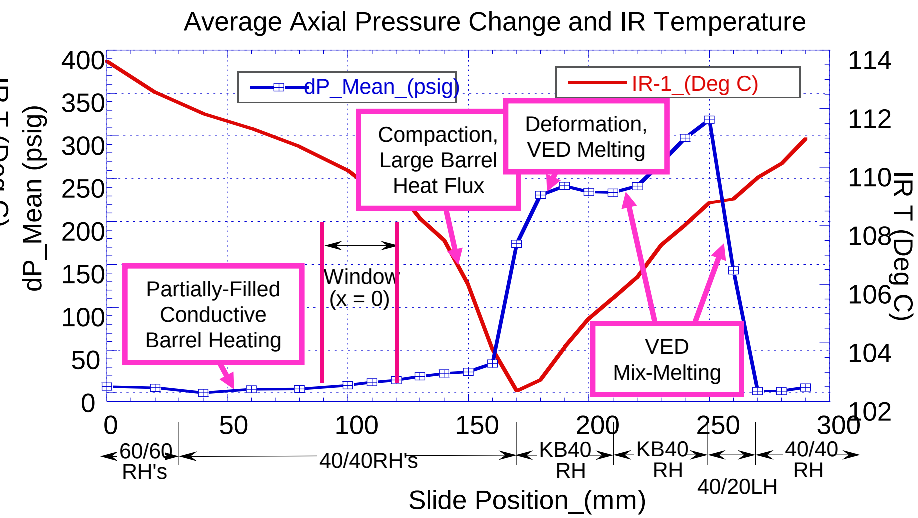
Melting Mechanisms: Impact of Process Conditions – RPM, Q/N LDPE/HDPE Pellet Melting – ZSK 40mm:P/T Mapping



27Kg/Hr. (60PPH), 60RPM
Q/N = 1.0, Mode #1 High Fill



27Kg/Hr. (60PPH), 90 RPM
Q/N = 0.67, Mode #2 Low Fill

Ref: Wetzel ANTEC 2002

T_{MELT} = 127C

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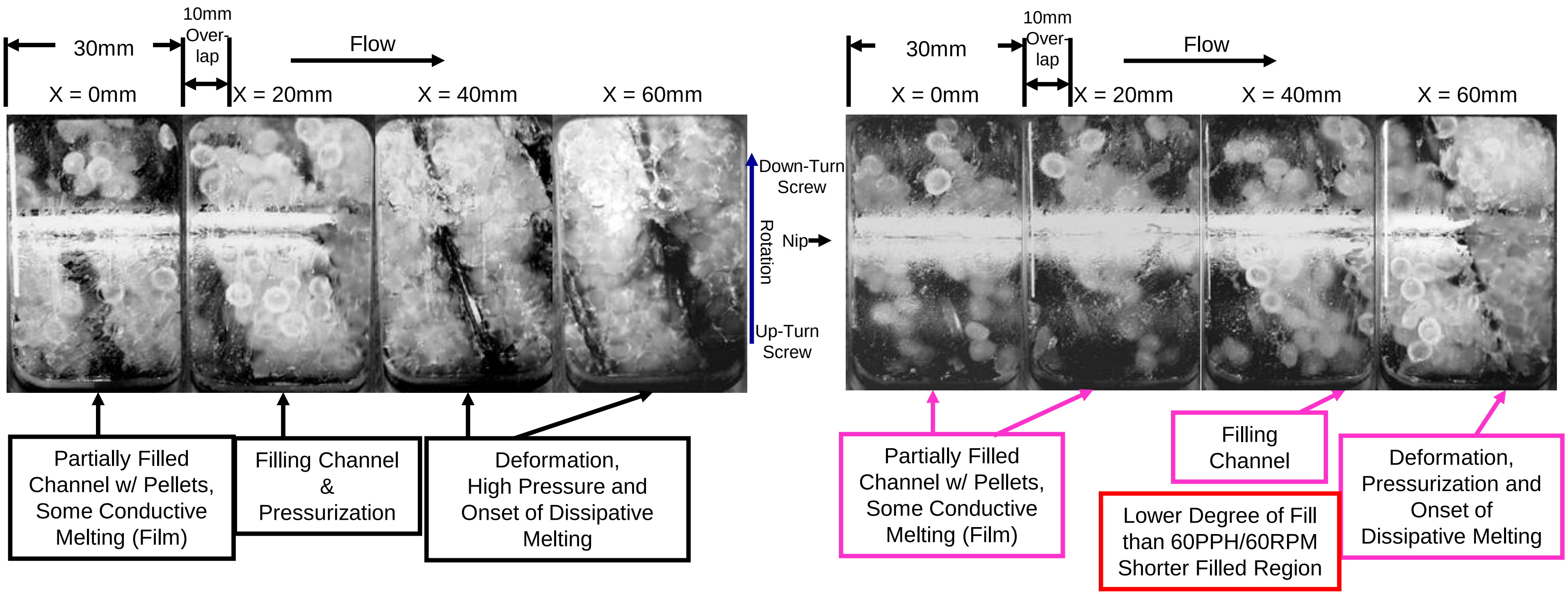
LDPE Melting Mechanisms: Visualization in Conveying Zone Impact of Process Conditions – RPM, Q/N



27Kg/Hr. (60PPH), 60RPM
Q/N = 1.0, Mode #1 High Fill

27Kg/Hr. (60PPH), 90 RPM
Q/N = 0.67, Mode #2 Low Fill

Ref: Wetzel ANTEC 2002

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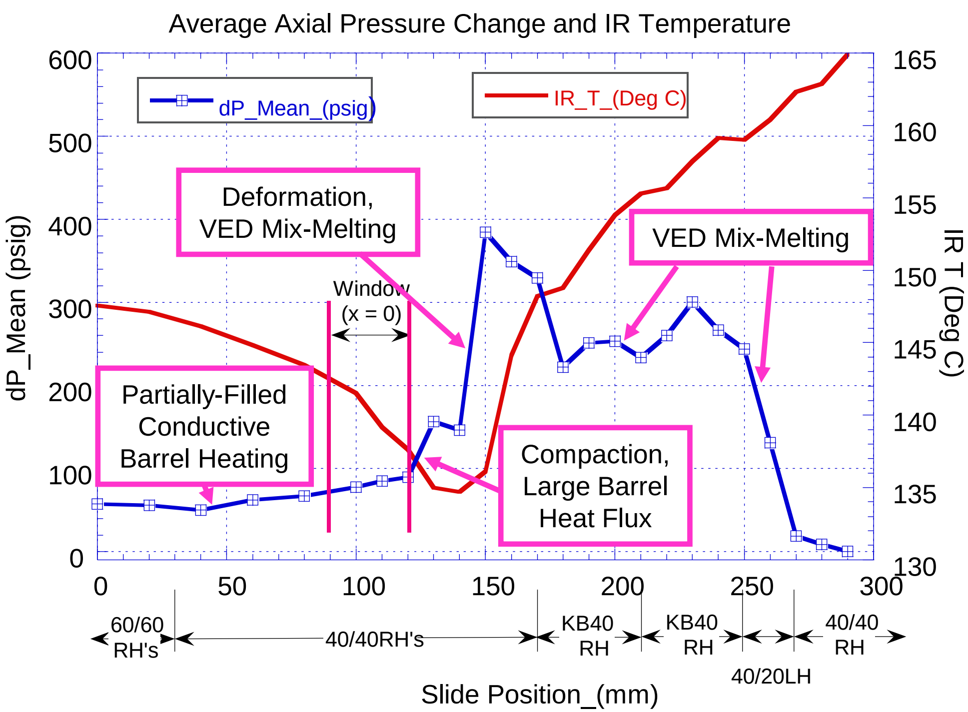
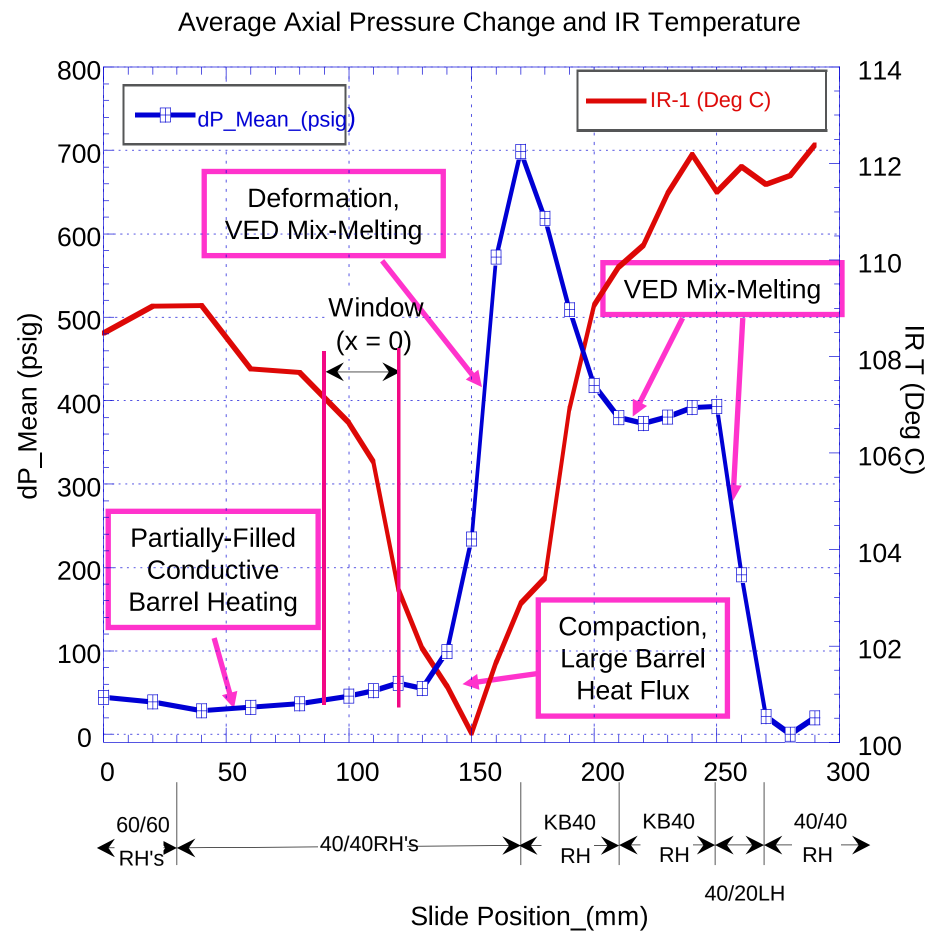
Melting Mechanisms: Impact of Process Conditions - RPM
LDPE/HDPE Pellet Melting – ZSK 40mm:P/T Mapping





27Kg/Hr. (60PPH), 60RPM
Q/N = 1.0, Mode #1 High Fill

55Kg/Hr. (120PPH), 120RPM
(Q/N = 1.0)

Ref: Wetzel ANTEC 2002

$T_{MELT} = 127C$

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LDPE Melting Mechanisms: Visualization in Conveying Zone
Impact of Process Conditions – RPM, Q/N

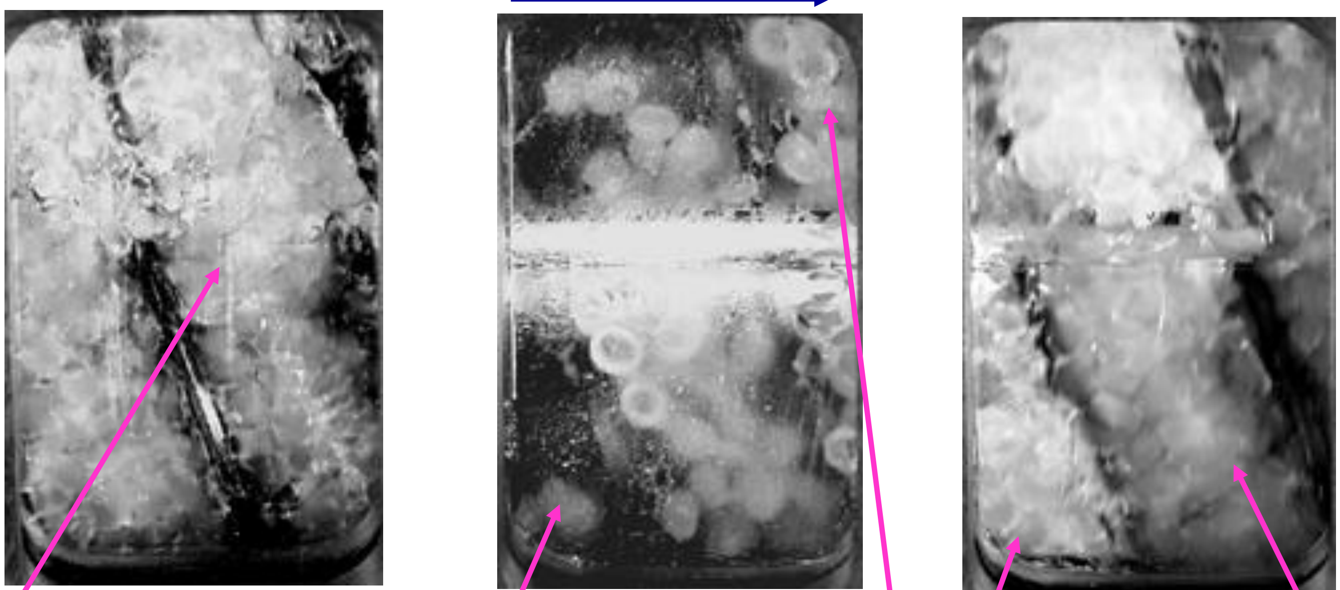
X = 40mm

Flow →

Down-Turn Screw

Nip →

Up-Turn Screw



Rotation ↑

27Kg/Hr. 60RPM
Q/N = 1.0, High Fill

27Kg/Hr. 90RPM
Q/N = 0.67, Low Fill

55Kg/Hr. 120RPM
(Q/N = 1.0), High Fill

Deformation,
High Pressure and Onset of Dissipative Melting

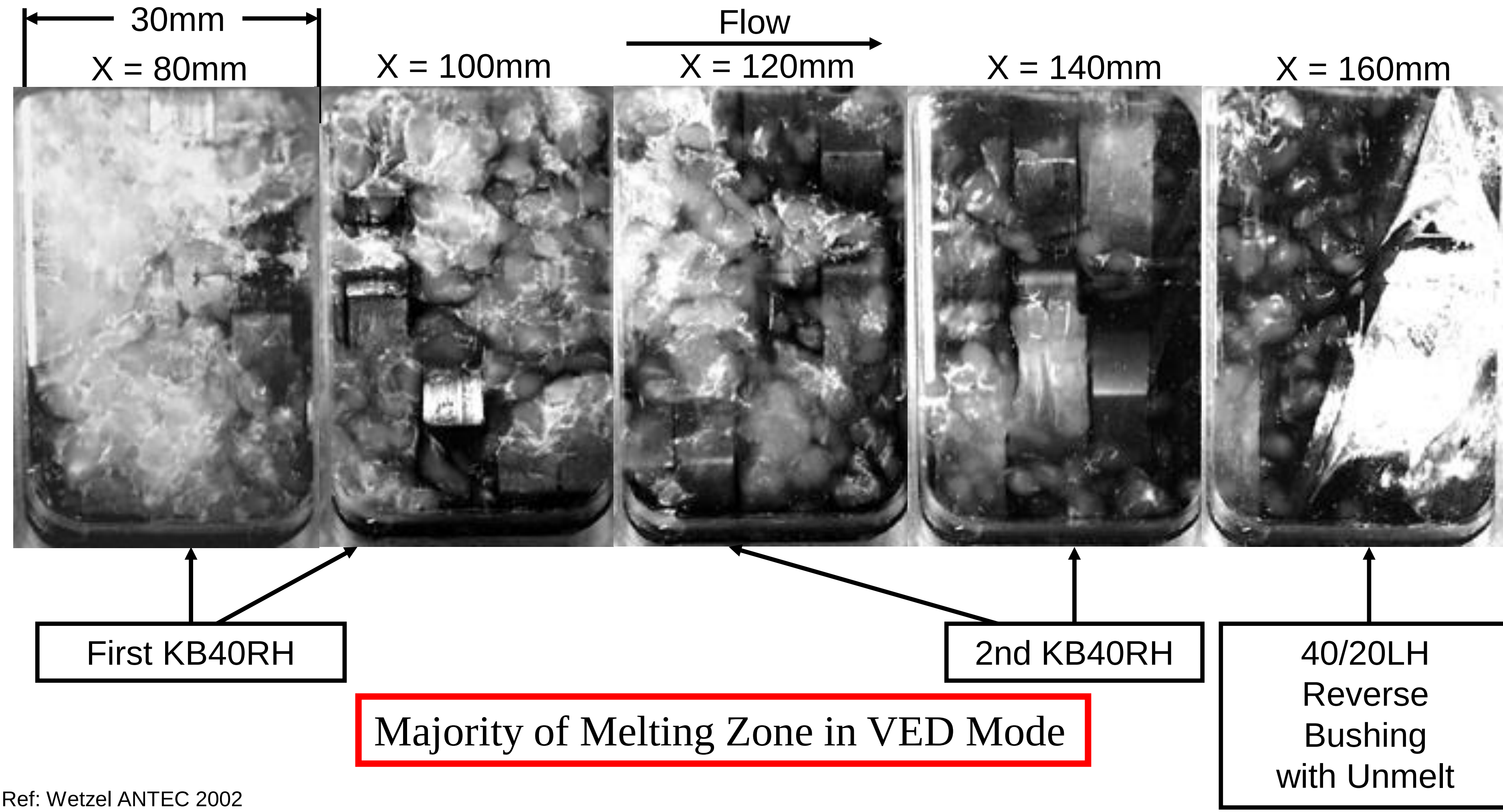
Partially Filled Channel

Filling Channel & Pressurization

Deformation,
High Pressure and Onset of Dissipative Melting

Ref: Wetzel ANTEC 2002

LDPE Melting Mechanisms: Visualization in KB Zone
Conditions: 60PPH/60RPM (Q/N = 1.0)



Majority of Melting Zone in VED Mode

Ref: Wetzel ANTEC 2002

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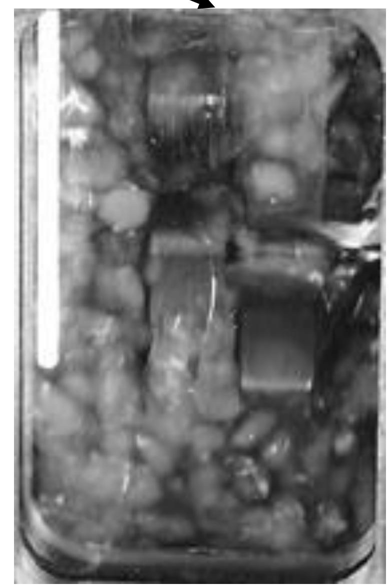
LDPE Melting Mechanisms: Visualization in KB Zone

Flow →

2nd KB40RH, X = 140mm

27Kg/Hr. 60RPM
Q/N = 1.0, High Fill
Mostly Melt
Pressure 275 psi

27Kg/Hr. 90RPM
Q/N = 0.67, Low Fill
Noticeable Un-Melt
Pressure 300 psi



55Kg/Hr. 120RPM
(Q/N = 1.0), High Fill
Significant Un-Melt
Pressure 400 psi

Ref: Wetzel ANTEC 2002

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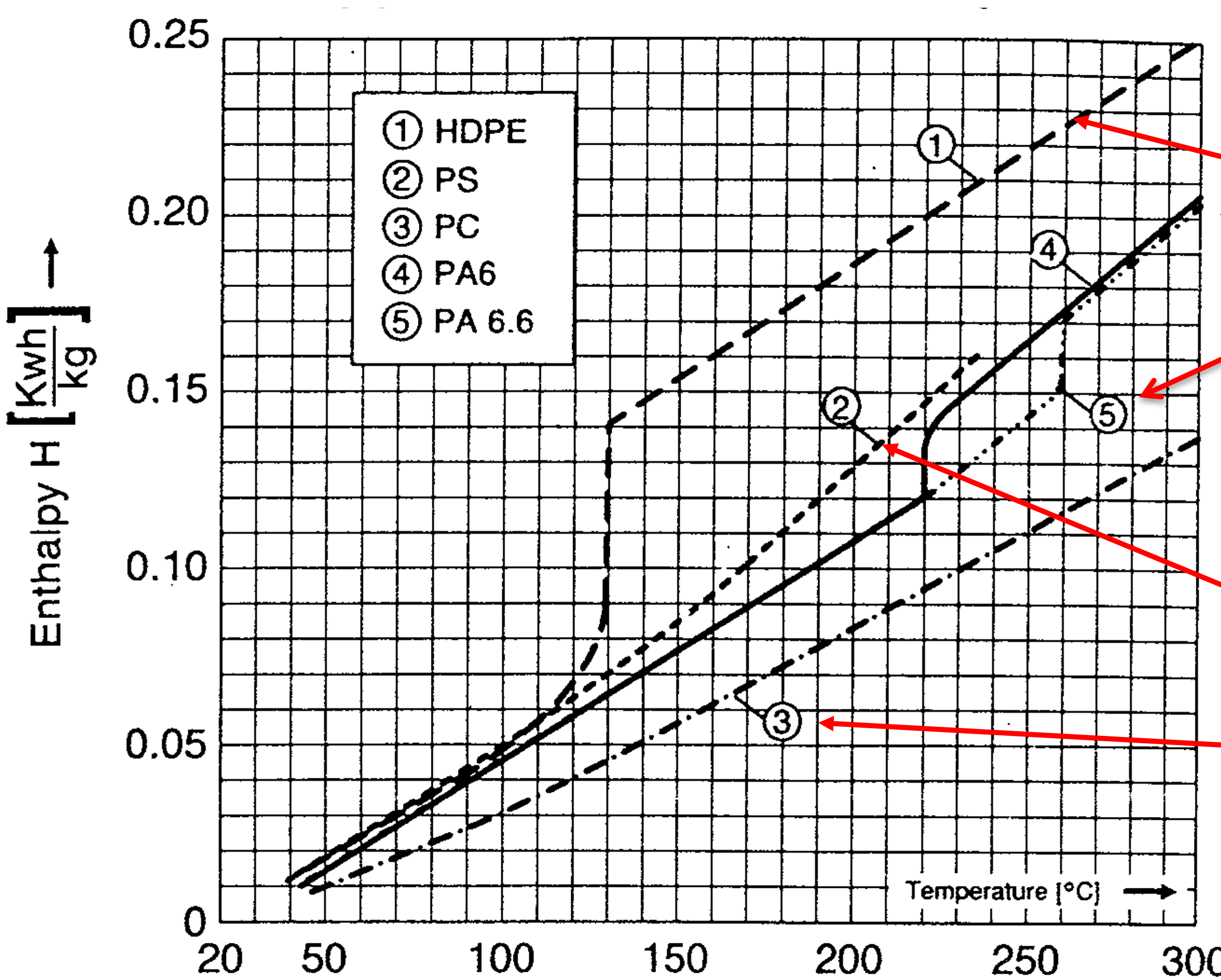
Melting Mechanisms: Impact of Material Characteristics



Crystalline:
HDPE
N_{66}Nylon

Amorphous:
Polystyrene &
Polycarbonate

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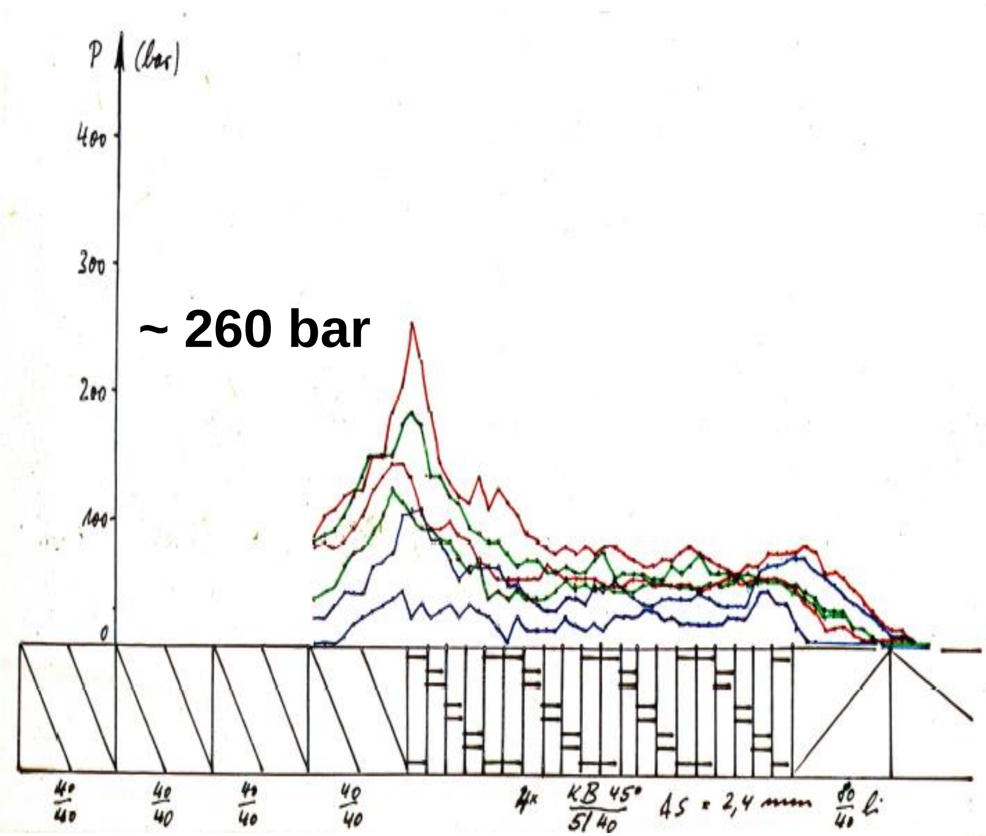
Twin-screw Melting Mechanisms: Impact of Material
Pressure profile – PE vs. N66

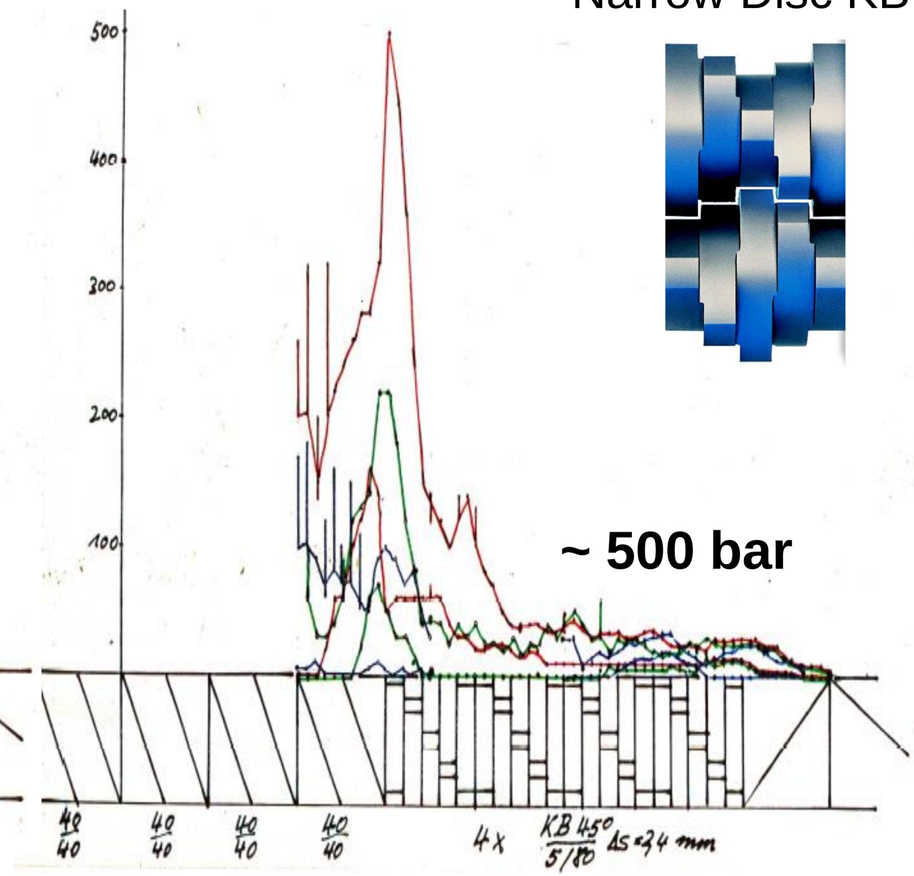
HDPE / 600 kg/hr/ 300 rpm
Active Pressure (Apex)



~ 260 bar

PA66 / 550 kg/hr/ 250 rpm

Narrow Disc KB



~ 500 bar

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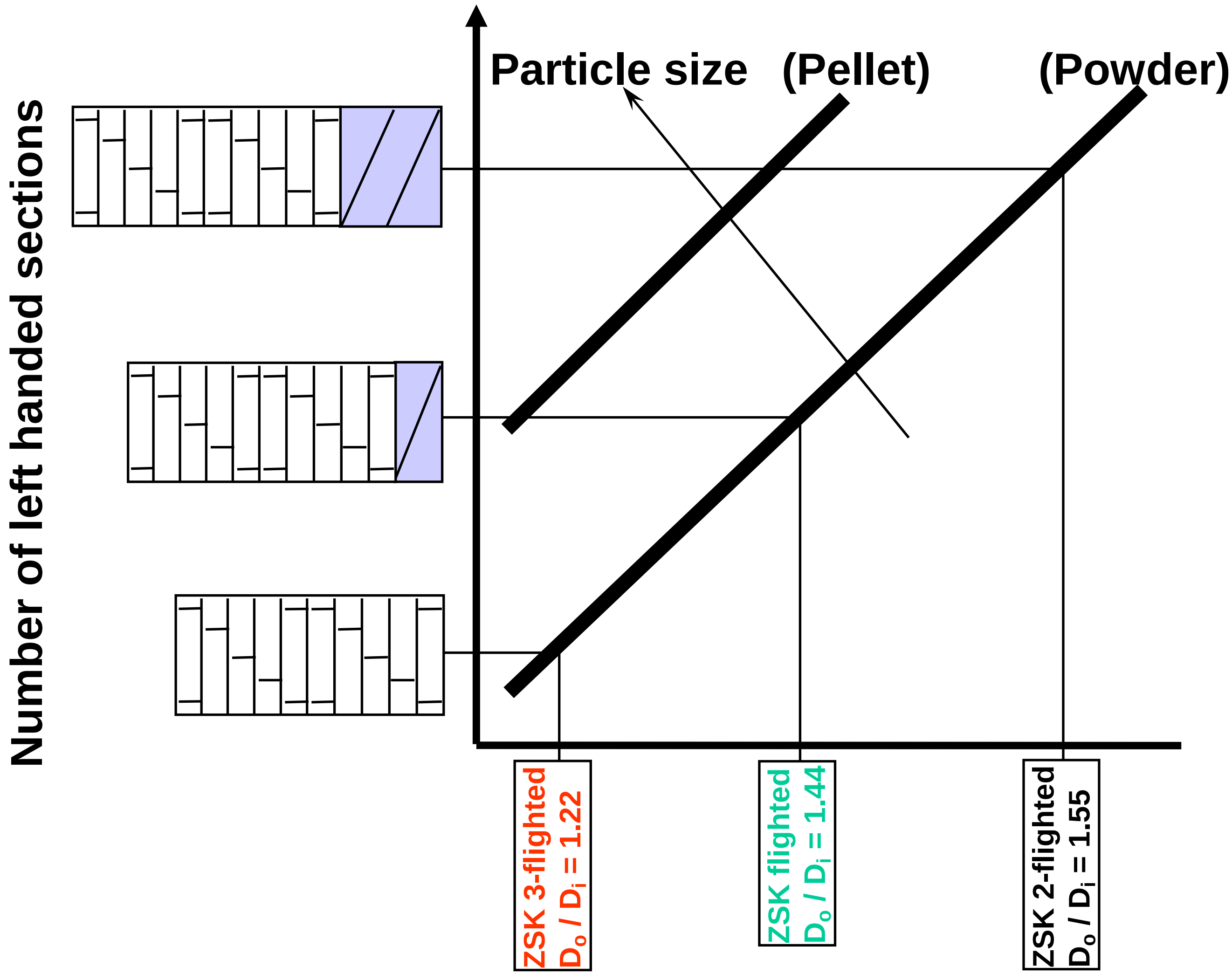
Twin-screw Melting Mechanisms: Layout of the Melting Zone Impact of Particle Size and Machine Geometry



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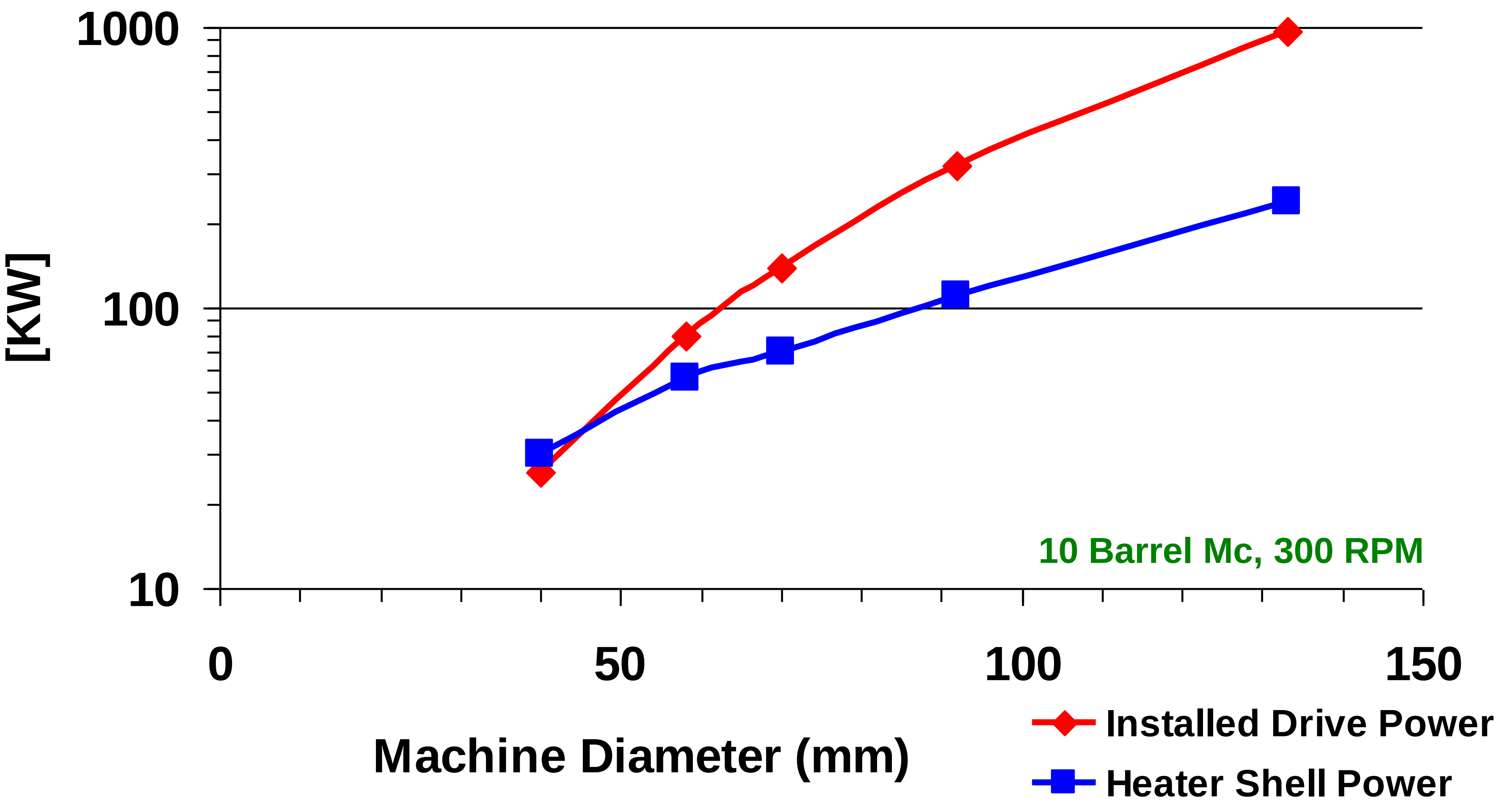
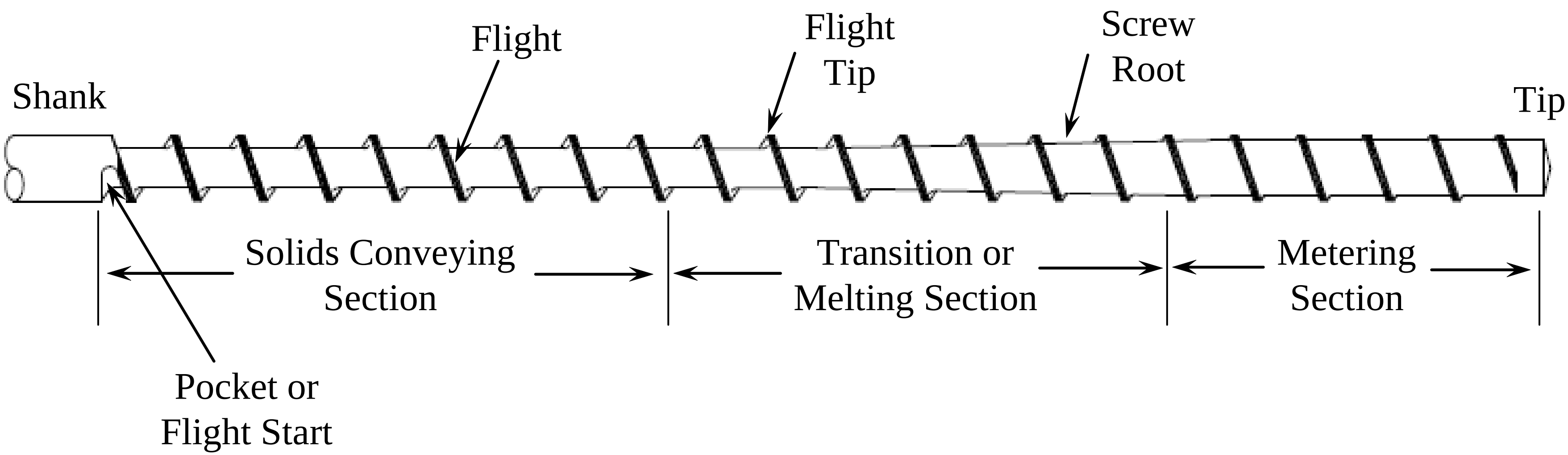
Melting Mechanisms:
Using Heater Power to Assist Melting



Solid to Melt Transition:
Impact on Downstream Processing
Metering/Pressurization

Geometric Specifications and Definitions



Specifications

Diameter: 0.75 inch up to 8 inch (larger machines possible)

Length-to-Diameter (L/D) Ratio: 8 to 40 (flow path only)

Meter Section Channel Height, 3 to 8 % of Diameter

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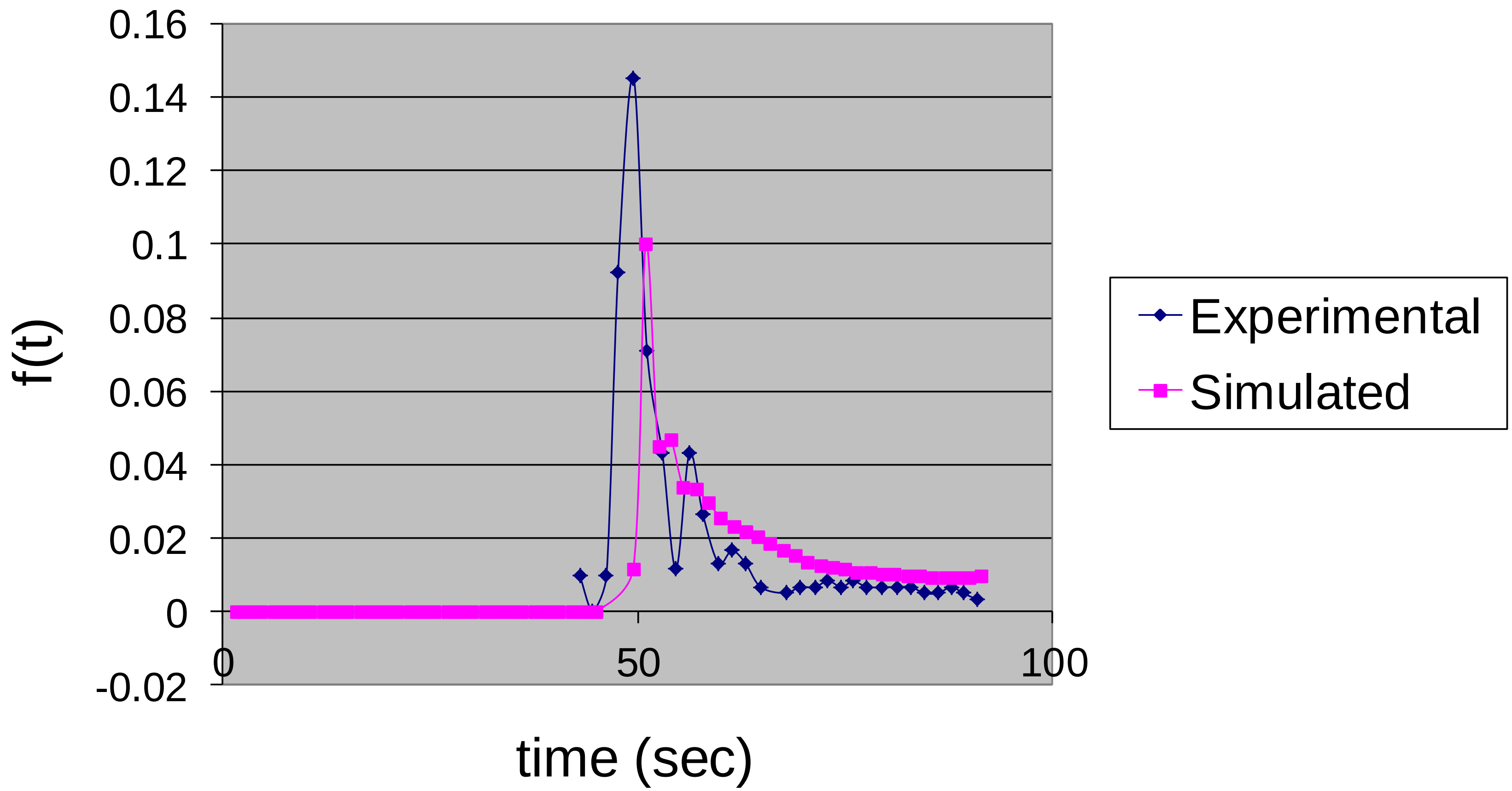
Meter Screw Dimension Pressure Drop Relation Ship

- Single Screws don’t built Pressure! They can push against a die restriction to very high pressures (higher than TSE)
- Meter Section Geometry resists flow from Die Pressure.
- Pressure induced flow is proportional to Meter Flight Height Cubed : H^3
- Rotational induced flow is proportional to the Metering Channel Depth H
- Rotational and Pressure induced flows are proportional to Meter Flight Width: W
- Pressure induced flow is inversely proportional to Meter Length

Solid to Melt Transition: Impact on Downstream Processing Degradation / Long Residence Time

RTD – Single Screw



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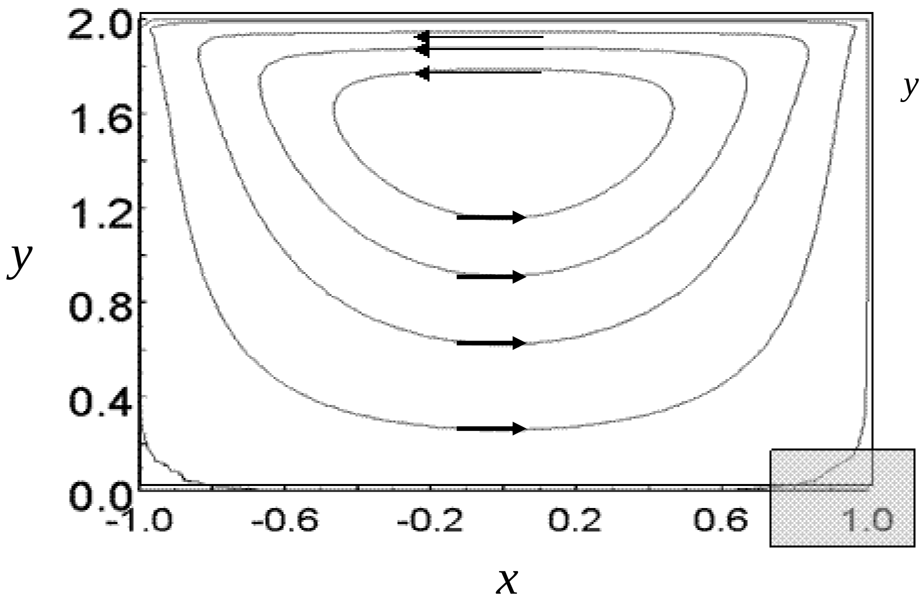
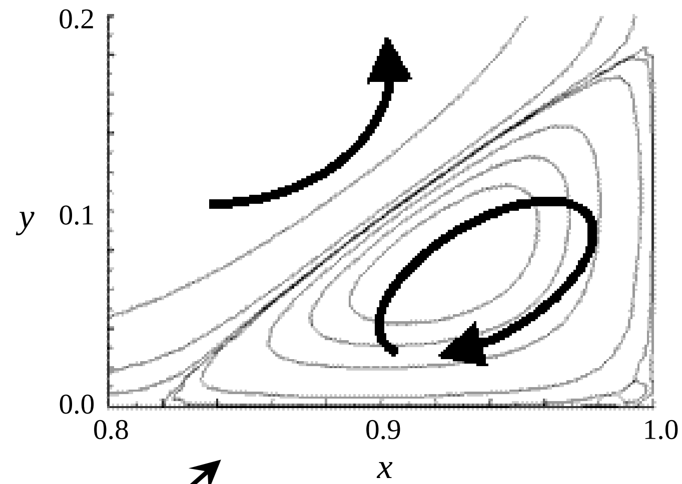
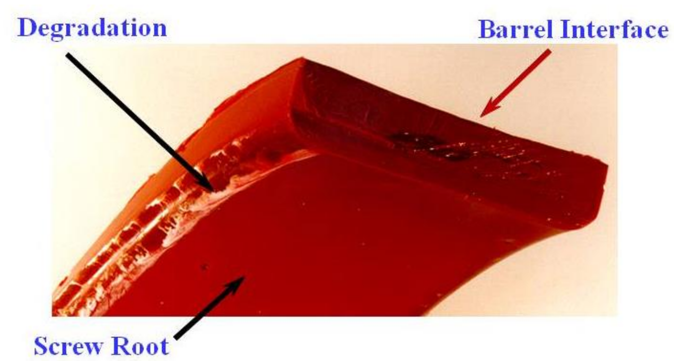
Carbon Specks and Gels in a Film Product

The degradation at the flight radii were caused by low flow or stagnant regions due to Moffat eddies

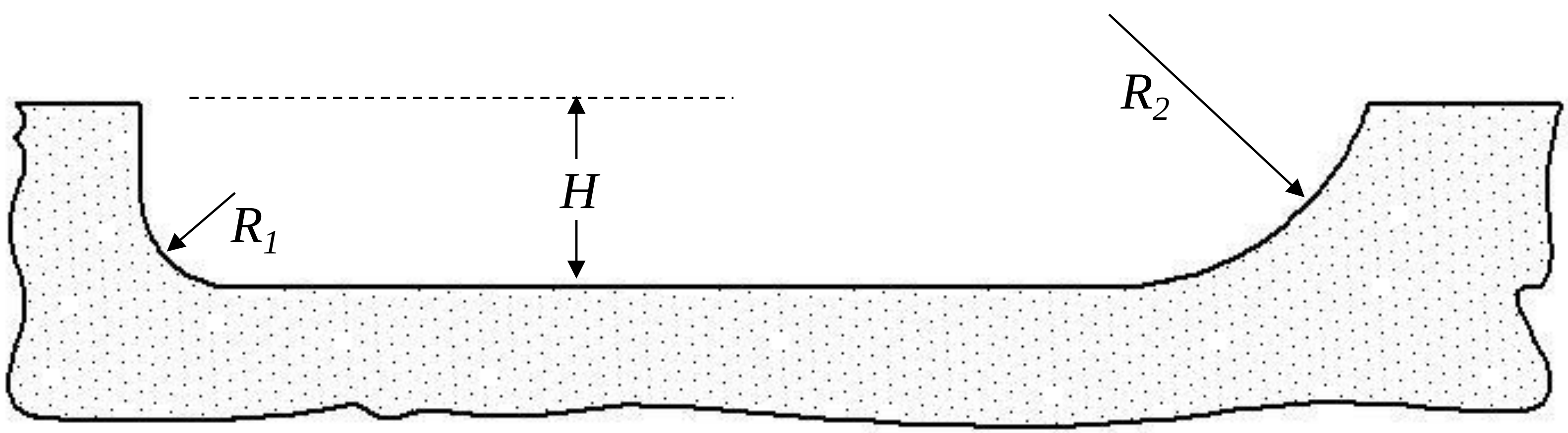






Flight Radii Size Recommendation

Screw Section	Flight radii to channel depth ratio Range	My Recommendation for LLDPE resin
Solids conveying	0.25	0.25
Transition section	Blend radii sizes from the solids conveying section to the metering section.	Blend
Metering	0.5 to 2.5	1 to 1.5



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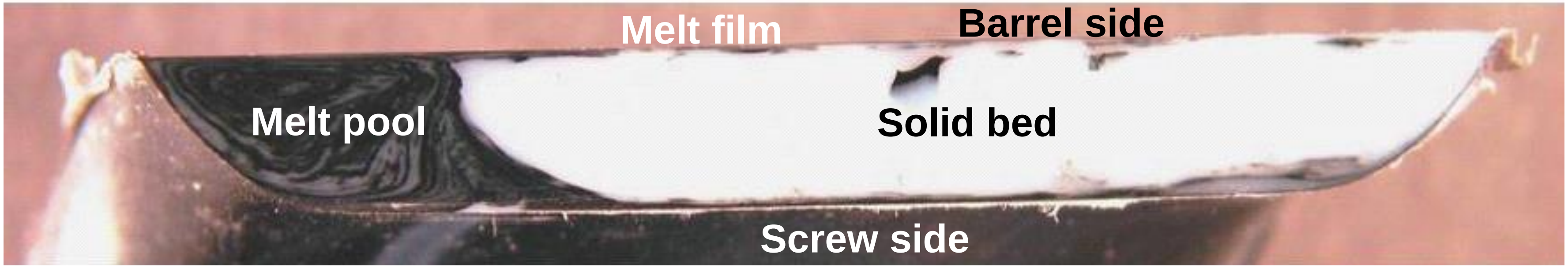
Summary: Single Screw Melting Process
Solid Bed Breakup and Residence Time Issues



- Solid bed breakup, unmelt, is a result of flow induced stress under the thin weak almost melted solid.
- Unmelt can be homogenized using high shear mixers or High Performance Screws.
- Long Residence time is major cause black specks and gels.
- Screw channel should be designed to eliminate Moffat eddy.
- Meter section must be in control: full, with pressure gradient decreasing from the die to the melting zone.
- Screw does not build pressure, it resists pressure flow caused by the die pressure.

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Summary: Twin-Screw Compounding Melting Mechanisms

Heating the barrel

- ❑ Least desirable option
- ❑ Can cause premature melting in conveying zone
- ❑ With increased size of extruder this heating effect will be reduced because the surface to volume ratio becomes less and less

Could be influenced by:

- ❑ Heating of the barrels
- ❑ Insulation of the barrels
- ❑ Heating of the screw shaft

Friction

- ❑ Internal friction of the powder
- ❑ Friction and shear stress in the narrow gaps, e.g. in the kneading blocks
- ❑ Shear stress between the molten and the solid parts

Could be influenced by:

- ❑ Screw Profile (kneading blocks)
- ❑ Screw speed
- ❑ Feed rate

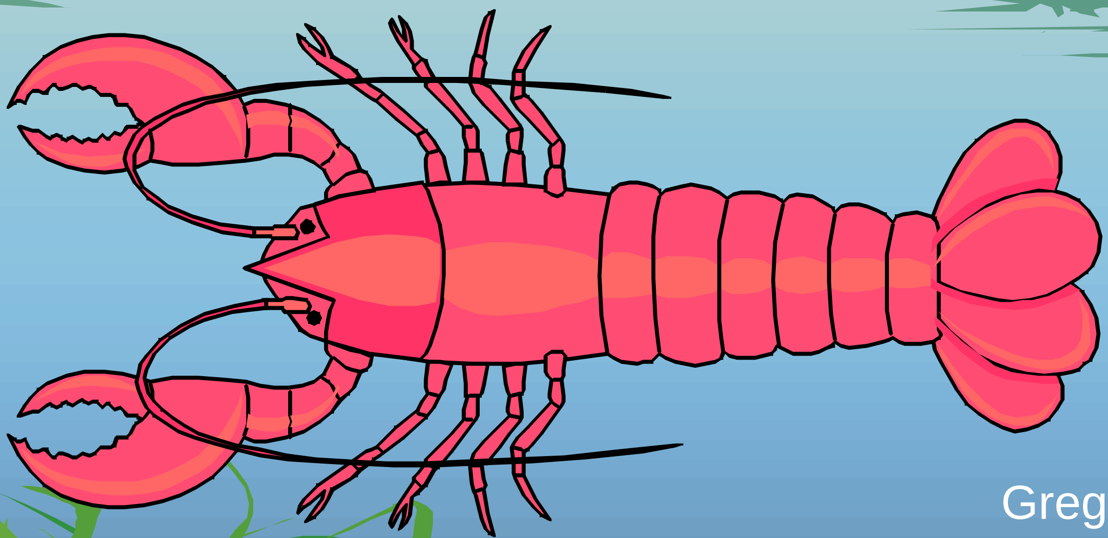
Heat Transfer

- ❑ The polymer melt is wetting the un-molten parts, which therefore will start to melt at its surface.

Could be influenced by:

- ❑ Screw Profile (mixing)
- ❑ Residence time (length of the extruder)

That's All Folks



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Thank you very much for your attention.

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