The Extruder
A look inside the "Black Box"

By

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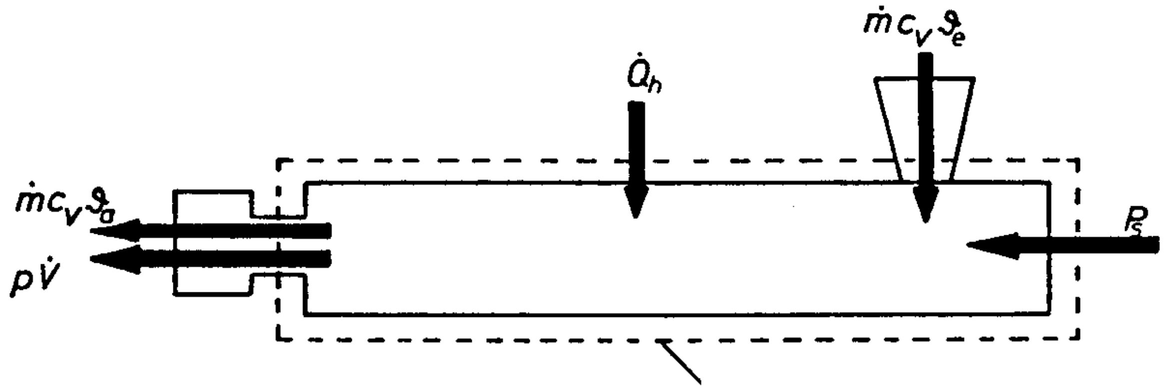
Outline

- Introduction
- Rheology
- Visualization with Color Rubber
- Empirical Assessment
- Conclusion

Introduction
Extruder Energy Balance

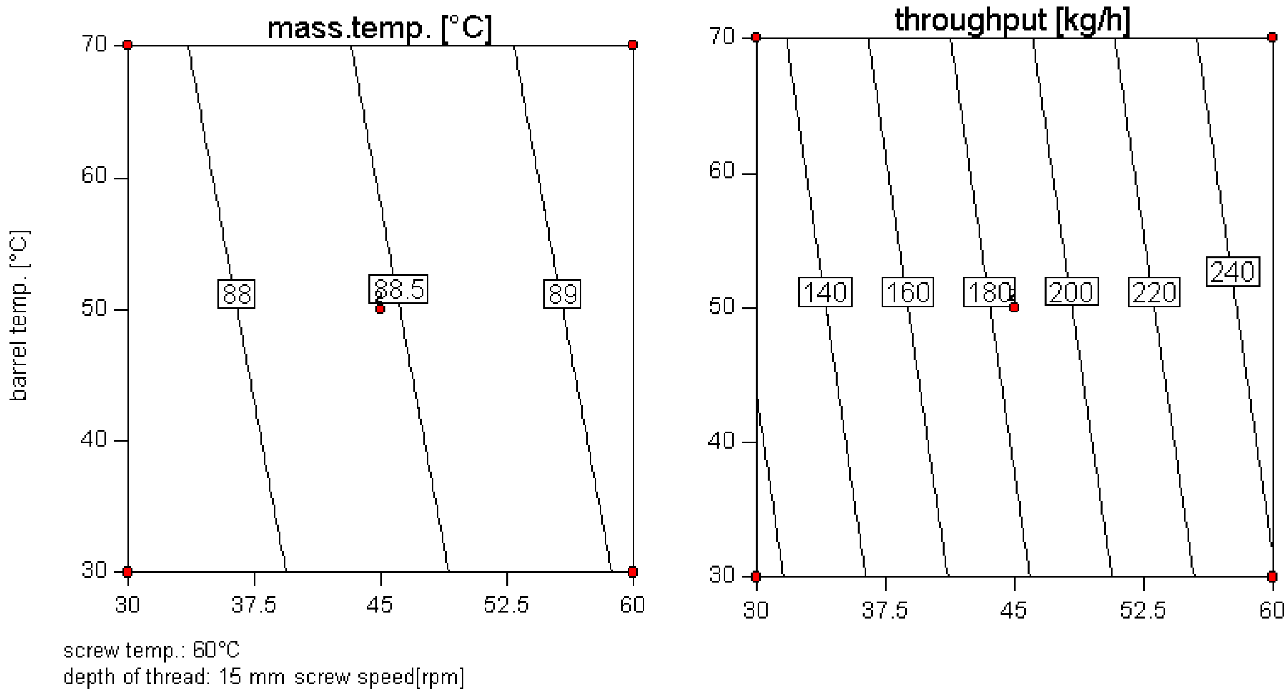
- **Input / Output Measurable to identify the capability and efficiency of an Extruder**
  - Source: Menges, Limper (1)



$$P_s + \dot{Q}_h = \dot{m} c_v \Delta\vartheta + \dot{V} p$$

Introduction
Model Theory

- **Empirical Models predict each of the energy balance parameters with respect to independent extruder settings.**
  - **The models are only valid if confined to the experimental boundary**



Introduction
Scaling Equations

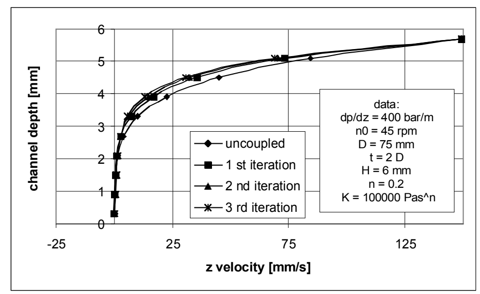
- **Based on the ratio of the diameters of the model extruder and the target extruder.**

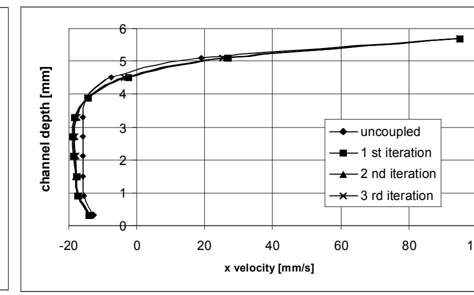
$$\text{New Value} = \left(\frac{D_{\text{New Screw}}}{D_{\text{Model Screw}}} \right)^{n} \text{x Model Screw Value}$$

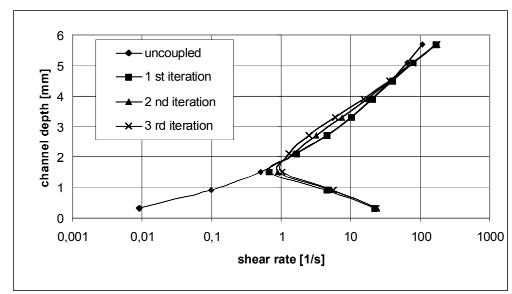
Value	n	Value	n
Flow	2	Speed	-0.5
Temperature	0	Flight Depth	0.5
Pressure	0	Pitch	0
Power	2		

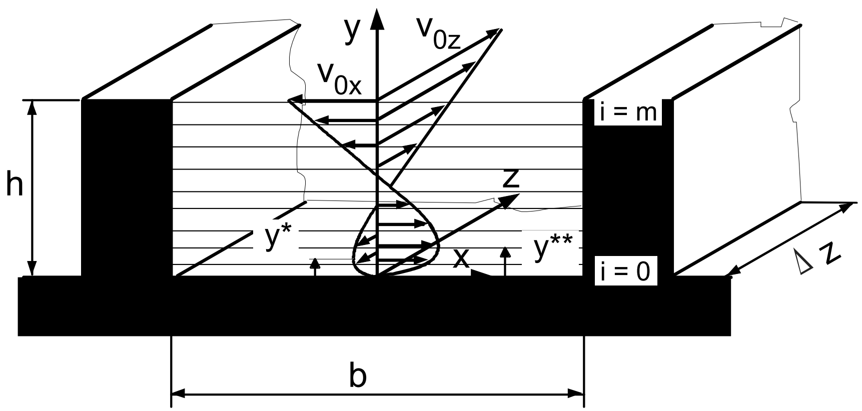
Introduction
Simulation

- **Simulation is the next step, but “Power Law” is used as a basis for calculations.**
  - **The “Power Law” is a mathematical description of experimental reuslts and not a “Law” ----- better use: Power equation!**









Introduction
Purpose of FEM-Simulations

- **The reason for simulation and prediction of extruder processes**
  - **Establish Process window**
  - **State of Material at Die**
- **Expand Experimental boundary beyond Model Theory.**
- **"Single Hit" manufacture of a Die using predictive Equations.**
- **This requires a intimate understanding of the Extruder: we would say a look into the "black box"**

Glass Window Extruder: [Source: Compuplast]

Rheology
Description of Flow

- **The Power Equation [often referred as "Power Law"] does not fully describe, what is observed in experiments**
  - **Slip flow for example**
- **The Equation does not describe the velocity distribution in a flow channel for a non-newtonian fluid accurately.**

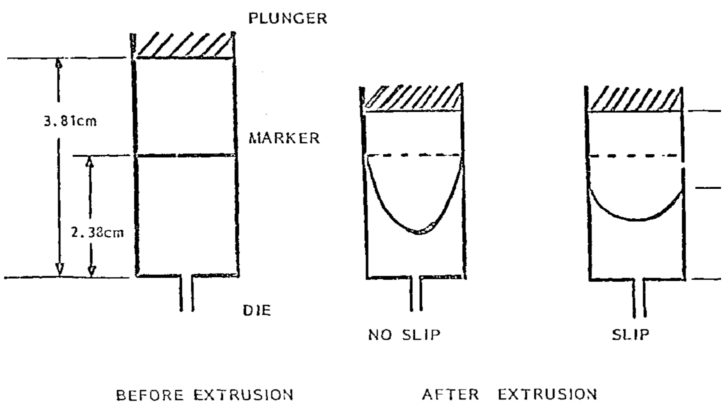
Rheology

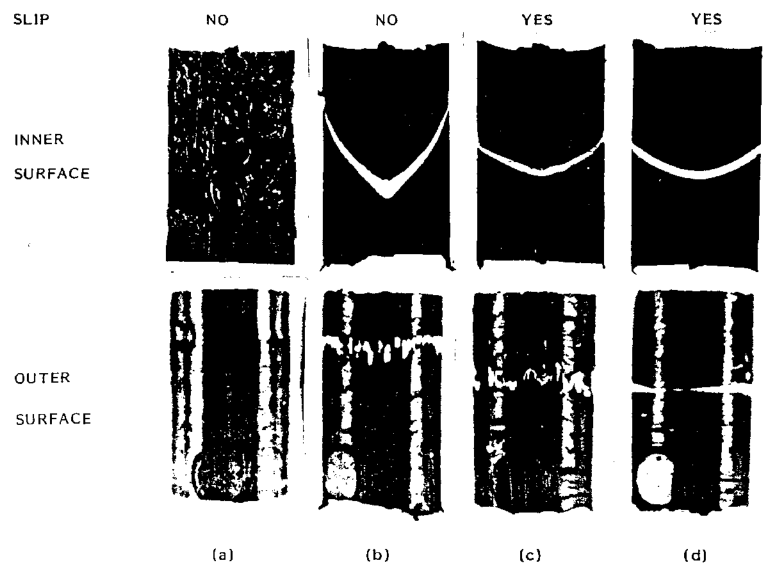
Measurement Devices for Viscosity

- **The mathematical description of data using the power equation, and**
- **the usage of equipment for measurement, which has other constraints, does not result in an understanding of the physical processes.**

Rheology
Visualization of Flow

- **Visualization of flow in a simple Capillary Reservoir Experiment**
    - **Source: J.L. White, et al.**

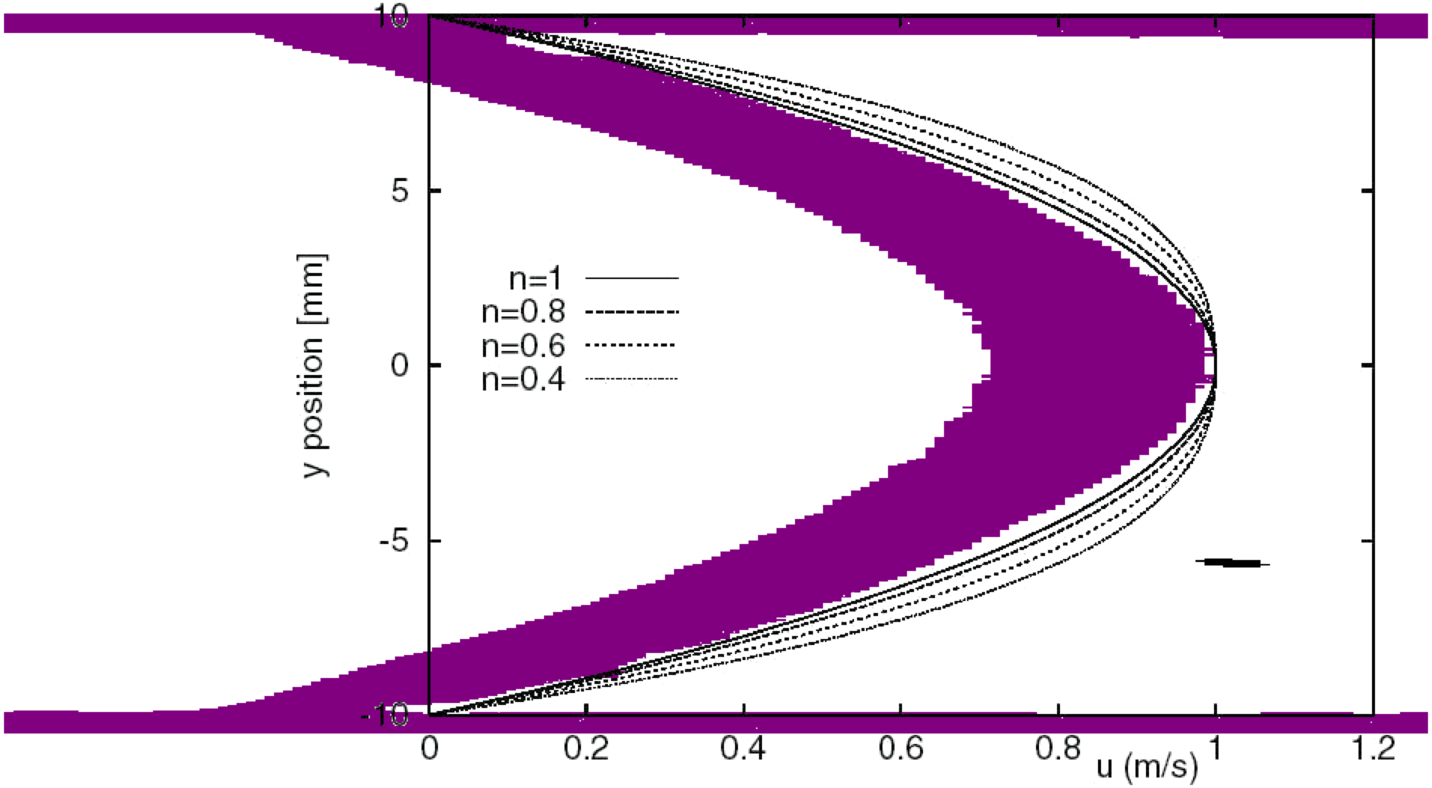




Rheology

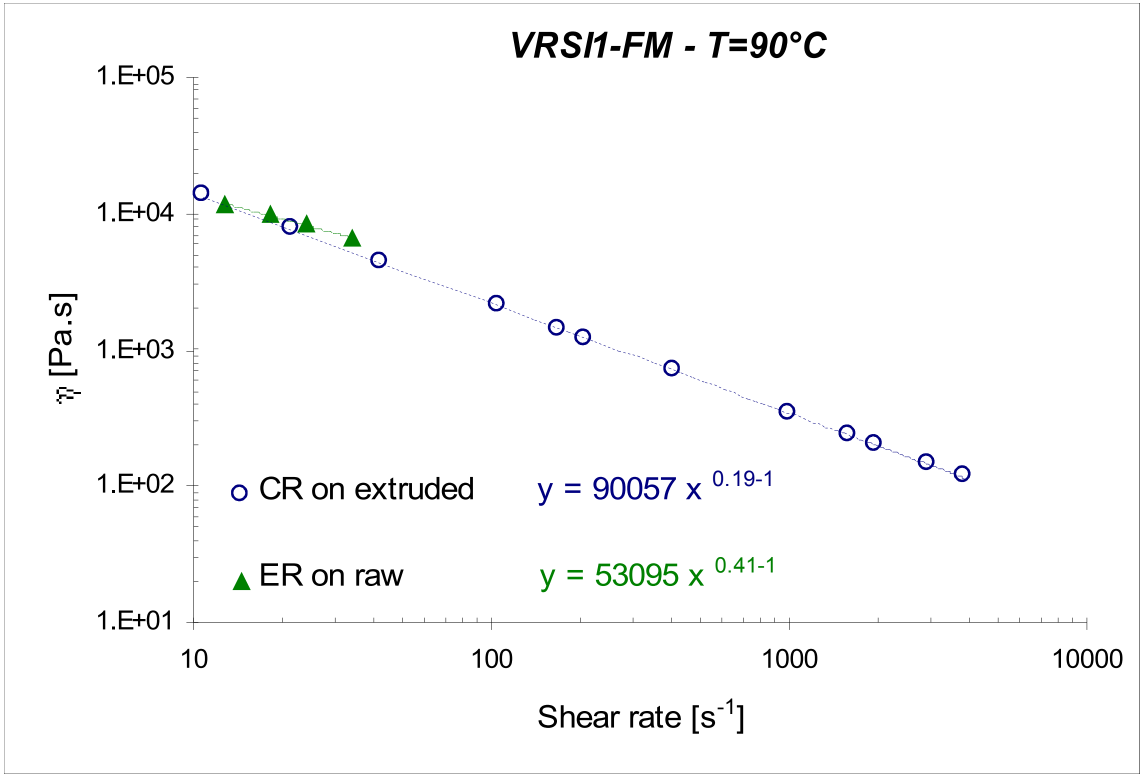
Velocity Distribution

- **Power Equation distributions do not match actual velocity distribution observed in experiment.**



Rheology
NR Compound

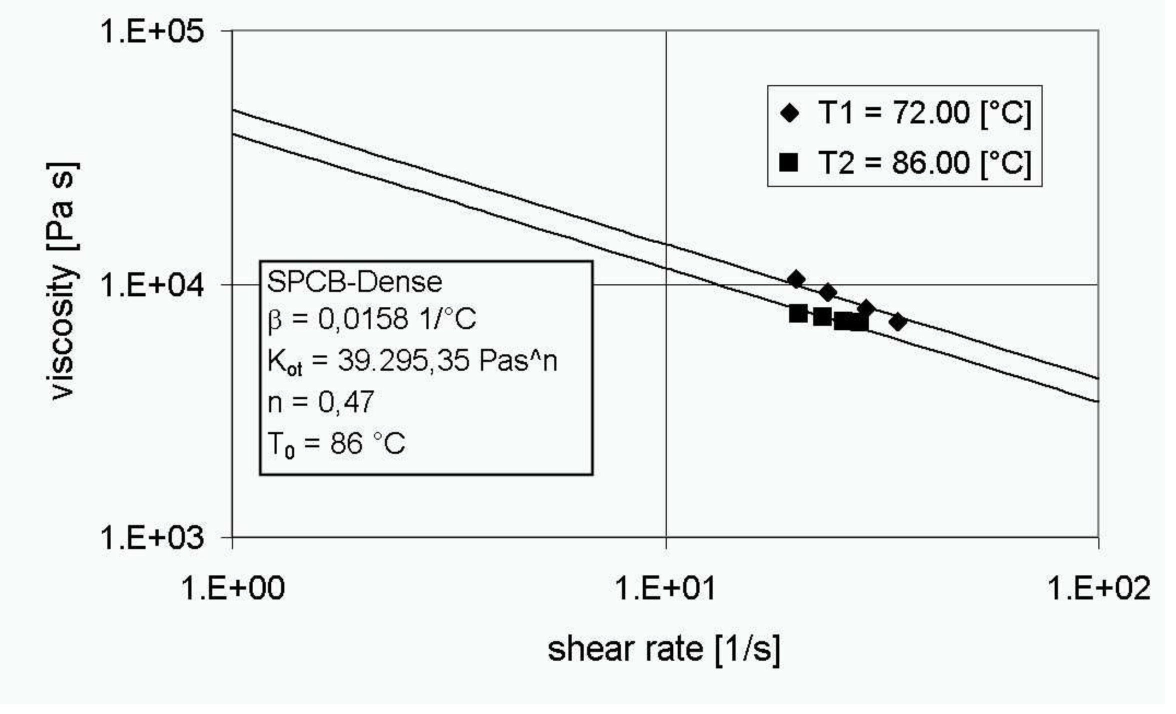
- **Comparison of Extrusion - [ER] and Capillary Rheometer [CR] result different equations (Variation of n).**



Rheology

EPDM Compound /Temperature Effects

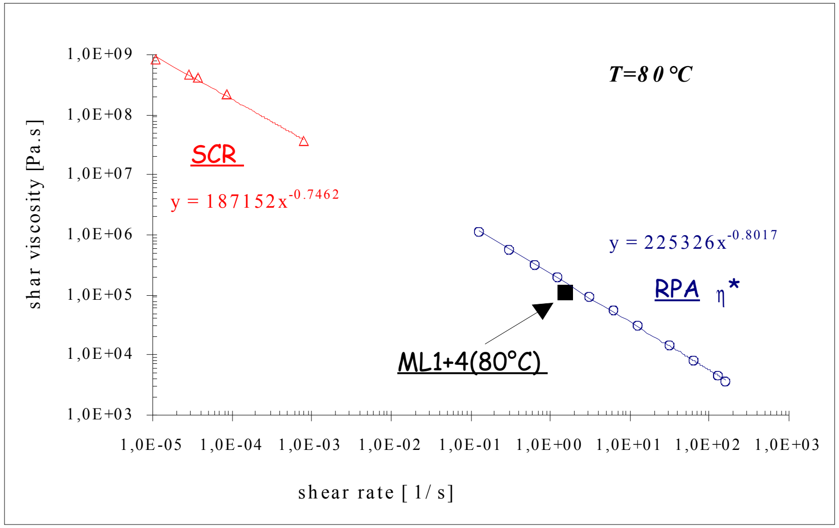
- **Depends on the test method used.**
- **Capillary rheometry [CR] does not always show an effect, where extrusion rheometry [ER] does.**



Rheology

Usage of fudge factors to mask the onset of slip

SI Tread Compound



Power equation mask the Detection of the onset of slip!

Methods:

SCR: Sliding Cylinder Rheometer

RPA: Rubber Process Analyzer

ML1+4: Mooney Viscometer

Power Law applicable for a wide range of shear rates

$$\tau = K \dot{\gamma}^{n}$$

Source: C. Barres & J.L. Leblanc, University of Paris, Polymer Processing and Rheology

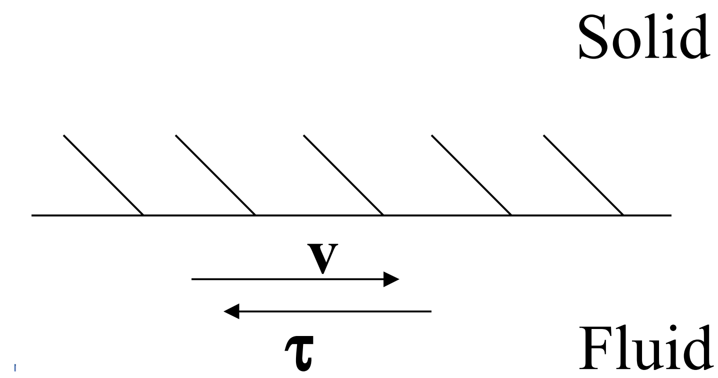
Material - Shear Viscosity

Rheology

Slipping laws

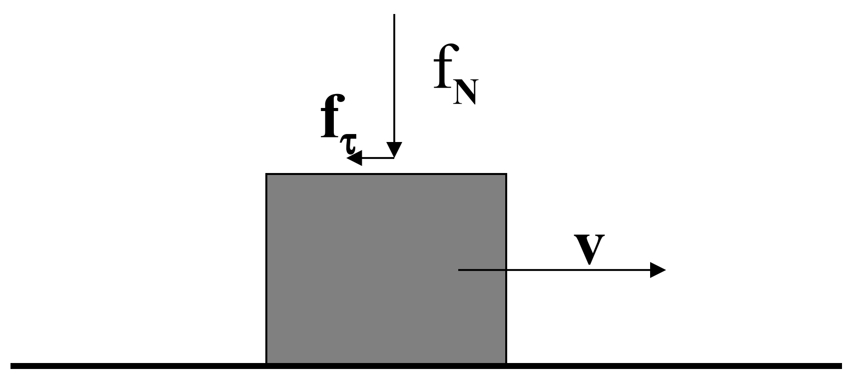
Navier slip

$$\boldsymbol{\tau} = -k_N \, \mathbf{v}$$



Coulomb slip

$$\mathbf{f}_{\boldsymbol{\tau}} = -k_c \, f_N \frac{\mathbf{v}}{|\mathbf{v}|}$$



Rheology

Pressure-dependent Navier slip law

$$\boldsymbol{\tau} = -\left(k_{NL} + \frac{k_{NH}}{1 + \frac{\|\boldsymbol{\tau}\|}{k_c . p}} \right) \mathbf{v}$$

For high values of p, tends to

$$\boldsymbol{\tau} = - (k_{NL} + k_{NH}) \mathbf{v}$$

For low vales of p, tends to

$$\boldsymbol{\tau} = - (k_{NL}) \mathbf{v}$$

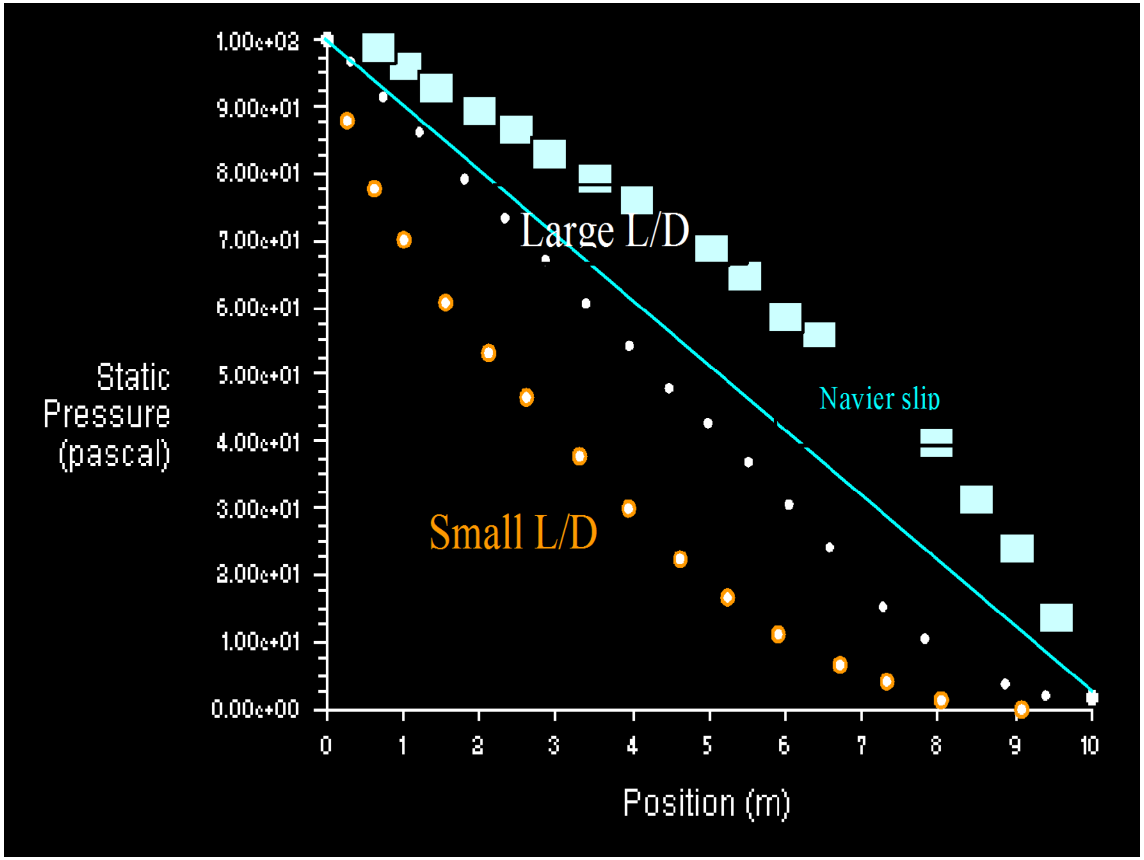
In between, manages transition. Typically, k_{NL} is a low Navier-slip factor and k_{NH} is high.

If $k_{NH} = \infty$ and $k_{NL} = 0$, then no slip at high pressure and perfect slip applies at low pressure.

Source: Jean-Marie Mareshal, Fluent

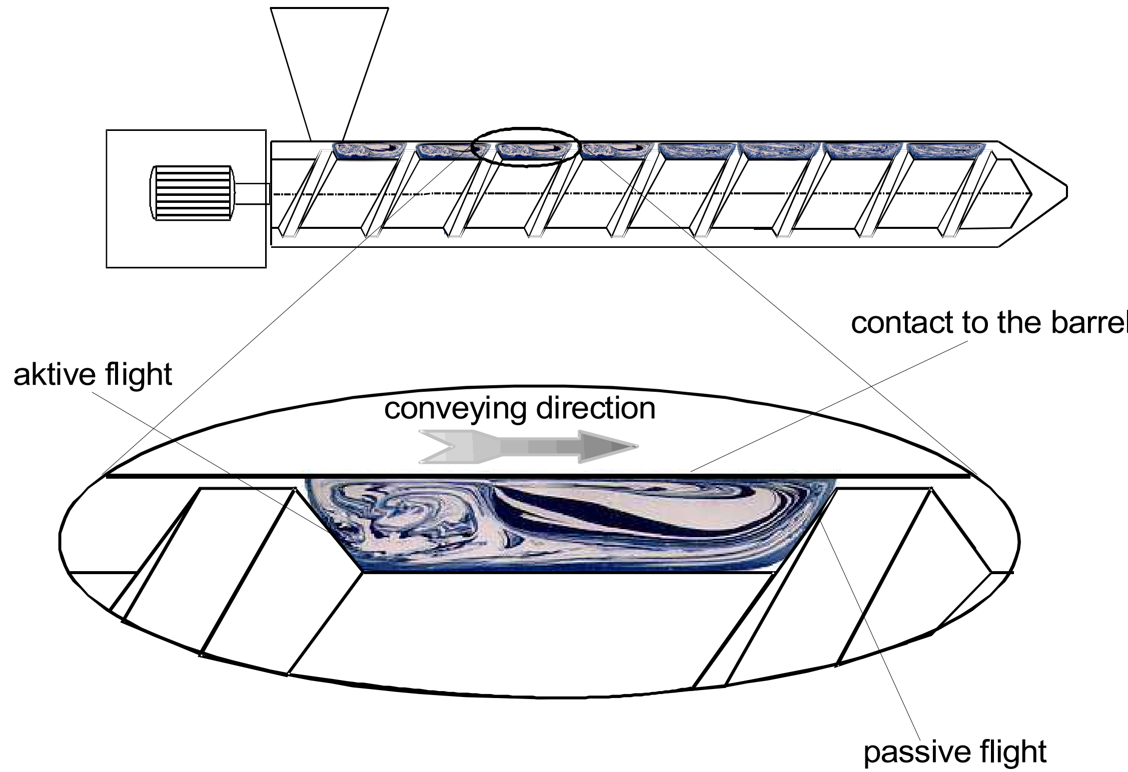
Rheology
Pressure Effects

- Pressure effect on slip



Visualization
Color Compound

- **Color mixing trial: Cross-section slice**



Source: Thomas Wilhelmsmeyer: Thesis

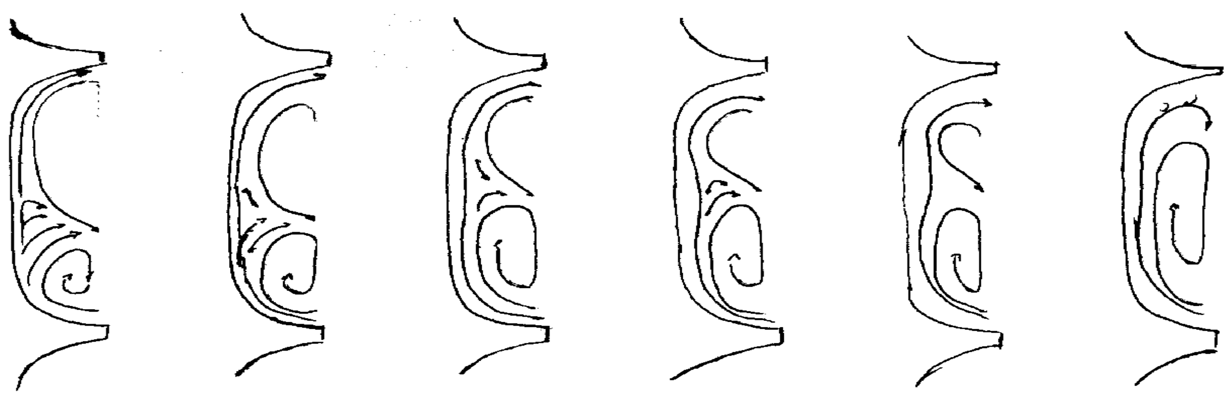
Visualization

Swirl diameter versus screw length and Flight Depth

Source: Cooperation with Cooper-Standard Automotive

Experimental Observed Mixing Effects

Visualization
Flow in the Extruder



One Slice represents 1 D

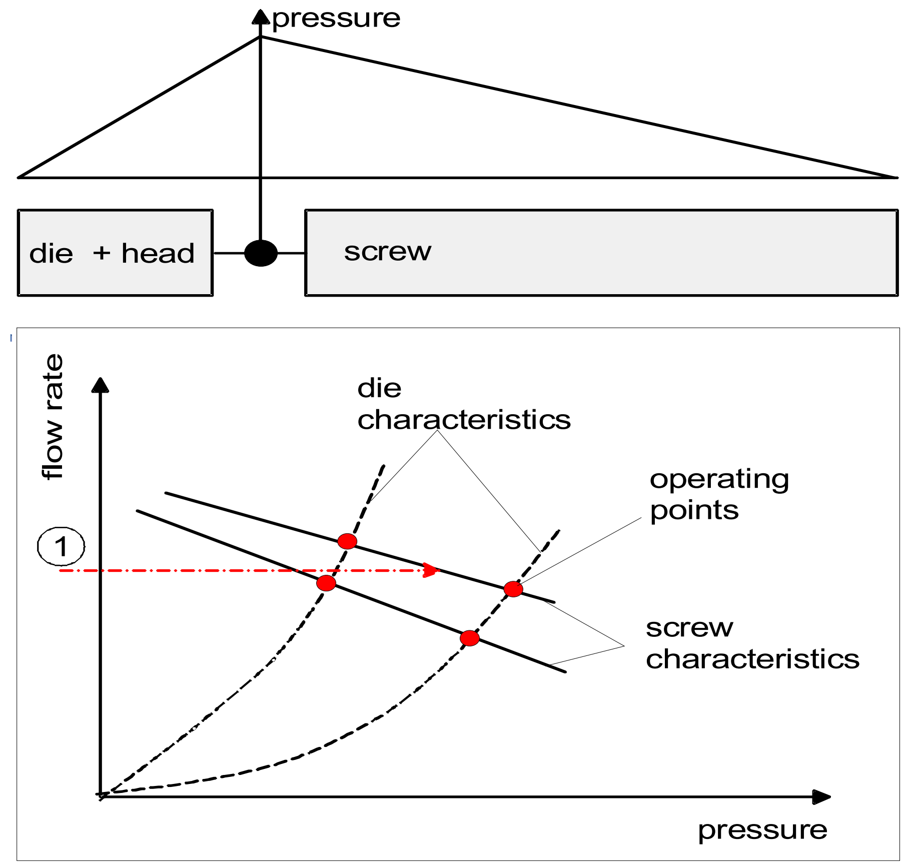
Visualization
Eddy Analysis

- **Cold core consumption has a pattern consisting of two swirl currents, which is not predicted.**
- **The Layer on the bottom of the screw is also not predicted.**

Empirical Assessment

Real System:

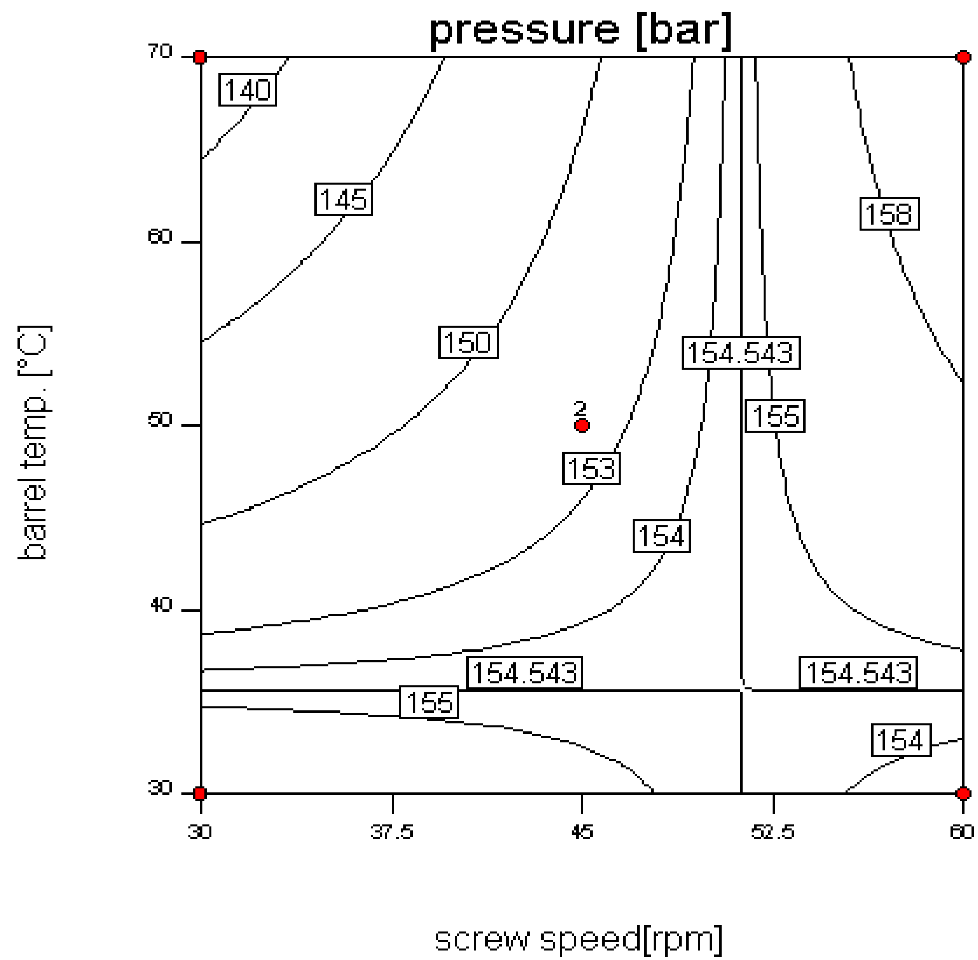
..to be Considered:
Screw Flow
& Die Flow...



Operating Characteristics

Empirical Assessment
Adiabatic Nature of System

- **Pressure stability over range of shear rates**



Empirical Assessment
Pressure Flow Calculation

- Flow balance neglecting leakage flow

$$\dot{V} = \dot{V}_{drag} - \dot{V}_{pressure}$$

- Normalizing with respect to drag flow

$$\pi_{pressure} = 1 - \pi_{\dot{V}}$$

Empirical Assessment

Flow Behavior

- **Volume flow fraction of drag flow**

$$\pi_{\dot{V}} = \frac{2\,\dot{m}\,F_d}{\rho\, n\, \pi\, D \cos(\phi)\, B\, H}$$

Where:	$\dot{m}$	**– Mass flow**
	D	**– Screw diameter**
	n	**– Screw speed**
	B	**– Channel breadth**
	H	**– Channel depth**
	ϕ	**– Flight angle**
	ρ	**– Compound density**
	F_d	**– Power law and B/H correction**

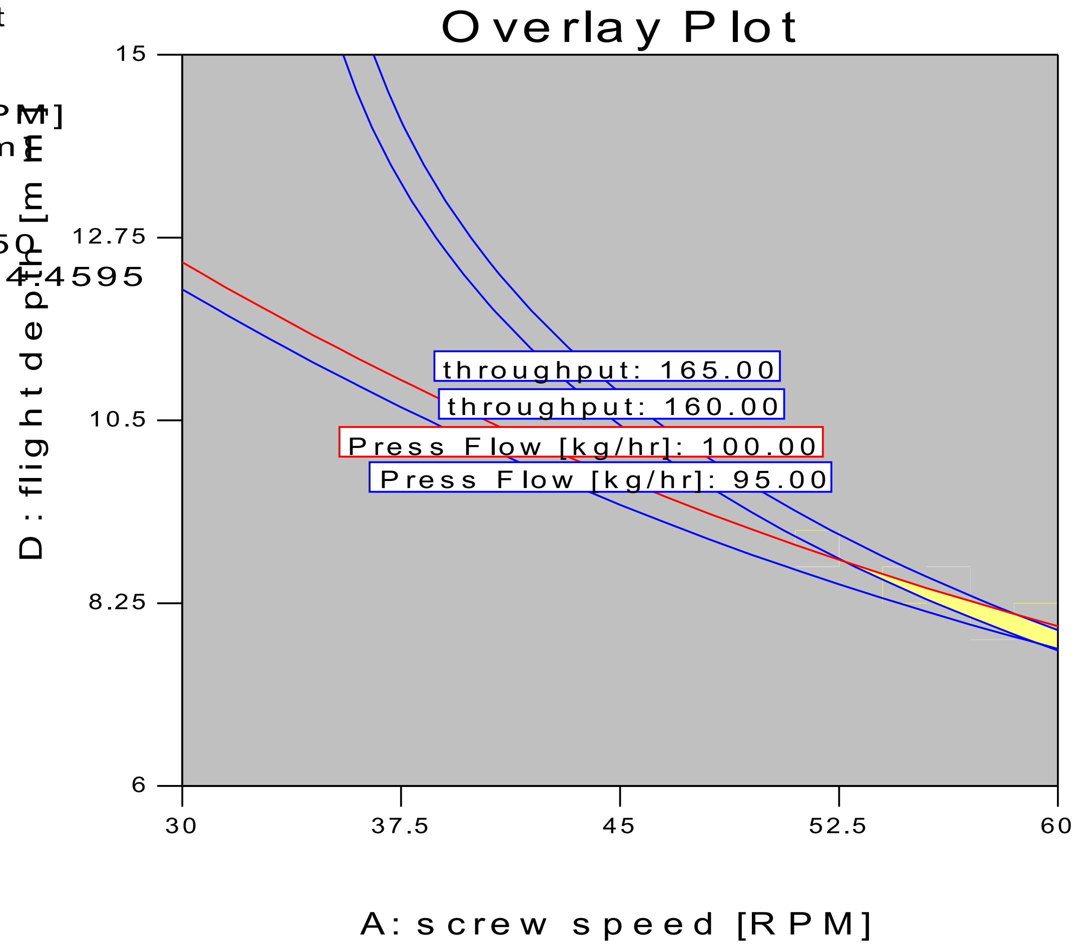
Empirical Assessment

Pressure Flow

DESIGN-EXPERT Plot

Overlay Plot
X = A: screw speed [RPM]
Y = D: flight depth [mm]

Actual Factors
B: barrel temp. [°C] = 50
C: screw temp. [°C] = 54.4595



Conclusion

- **The fundamental modeling of fluid behavior needs to be revisited**
  - **“Power law” vs. Newtonian Fluid**
  - **Slip versus Non-Slip Flow**
- **Information gained from Visualization techniques will improve the accuracy of Models [FEA]**
- **Empirical modeling allows the extraction of more information with the same amount of experimental data.**