Analysis of Free Surface Flow in Extrusion Film Casting Using Experiments and Simulations

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Motivation:

- Extrusion film casting is an important polymer processing operation for making films/sheets.
- VE-driven defects in extrusion casting such as edge-beading and necking, and process instabilities like draw resonance, are controlled by melt rheology, which in turn is controlled by the chain architecture.
- Excellent test case for free surface evolution.
- PE provides possibilities of using resins with different chain architectures.

Objectives:

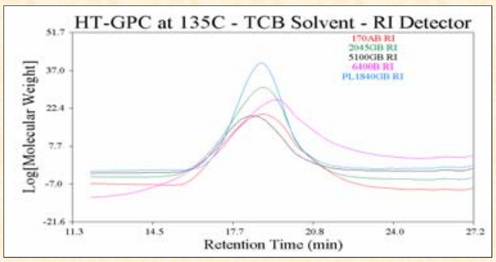
Our objective is to study the effect of *chain architecture* on *neck-in length and thickness distribution* of extrusion cast films using a combination of experiments and simulations.

Past Work:

- Key Theoretical Models for
  - for predicting the cast film thickness profile (e.g., Dobroth-Erwin, 1986)
  - for predicting the neck-in/edge beading defects associated with the process (e.g., Ito et al., 2003)
- 1D, 2D, quasi-3D numerical simulations for Newtonian as well as VE fluids have been utilized to study extrusion film casting.
  - Carley (Newtonian fluids, 1D)
  - D'Halewyn (VE fluids, 2D)
  - Debbaut (VE fluids, quasi-3D)
- An ALE based finite element method was recently validated for the simulation of polymer flow in abrupt contractions (Ganvir et al., 2007) and for simulations of flow with free surfaces such as in the case of extrudate swell (Ganvir et al., 2009).

Materials & Methods:

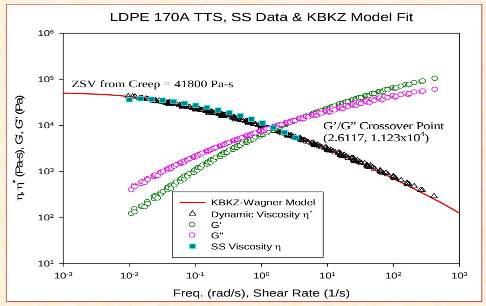
Materials (Dow PEs)	Methods
• LDPE 170A – LCB (branch-on-branch) • LLDPE Dowlex 2045G – SCB, ZN catalysis • LLDPE Elite 5100G – SCB; tiny amt of LCB – CGSS catalysis • Affinity PL1840G – SCB, some LCB – CGSS catalysis • HDPE DMDH6400 – Linear chain	• Rheology (MCR301/SER-ARES) – Steady shear – Transient/dynamic shear – Uniaxial extensional • Extrusion film casting – DSM microcompounder – Cast film accessory – 35 mm (W) x 0.4 mm (t) – 190ºC, 200 RPM – Take-up roll 120 – 4000 mm/min • Thickness/Neck-in measurement – Micrometer screw gauge – Snapshots from Neck-in videos

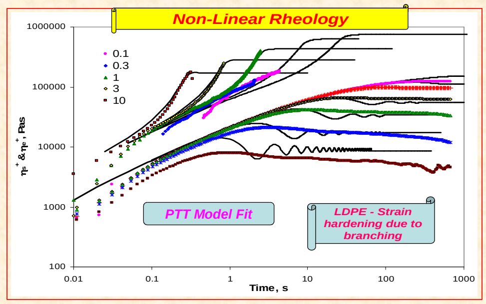


Material	PE Type	Mn	Mw	Mz	PDI	LCB/1000C
170A	LDPE	30600	185900	528400	6.07	3
2045G	LLDPE - ZN	46800	155200	491200	3.31	-
1840G	POP - CGC	52600	116100	224100	2.21	BDL
5100G	LLDPE - CGC	52200	156200	337200	2.99	BDL
DMDH6400	HDPE	9390	130100	833300	13.85	-

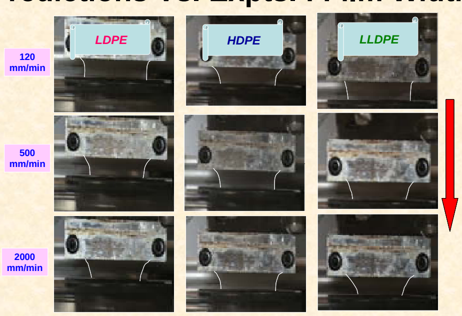
Rheology: Linear & Non-Linear

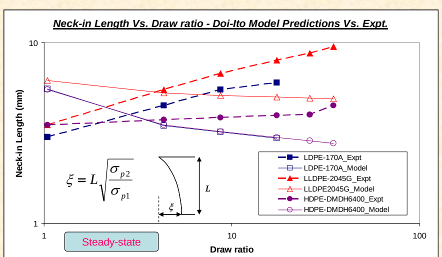
Example of rheological measurements and modeling





Predictions Vs. Expts. : Film Width





$$\xi = L\sqrt{\frac{\sigma_{p2}}{\sigma_{p1}}}$$

- Experimentally, for all PE's, the film neck-in length increases with increase in draw ratio.
- LLDPE shows maximum neck-in followed by LDPE and then by HDPE.
- Steady-state neck-in model proposed by Doi-Ito (2003) containing the KBKZ constitutive equation does not predict draw ratio dependence of neck-in.

ALE FEM Technique:

Lagrangian	Eulerian
– Easy memory tracking and no convective derivatives	– Looking at a fixed window (Typical of extrusion)
– No special treatment for free surface	– No mesh related problems i.e. no mesh distortion, etc.
– Faster simulation, reduced number of time steps	– Difficulties in treatment of convection
– High mesh distortion and need for frequent remeshing	– Special free surface treatment

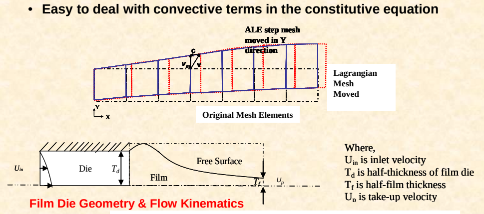
ALE

ALE - Kinematics

- **Computational mesh moves in an arbitrary manner, independent of the material motion**

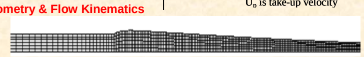
ALE Fractional Step Method

- **Lagrangian material motion (v) and mesh motion (v_m) are solved separately**
- **Convective velocity, $c = v - v_m$**
- **The variables are convected to account for mesh motion**
- **Easy to deal with convective terms in the constitutive equation**



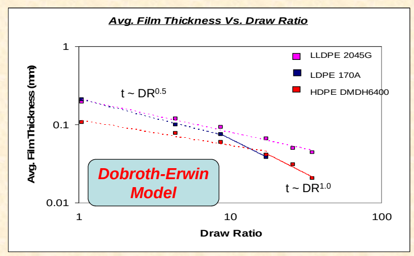
Where,
U_{in} is inlet velocity
T_d is half-thickness of film die
T_f is half-film thickness
U_o is take-up velocity

Film Die Geometry & Flow Kinematics



Typical Mesh for Cast Film Thickness Profile from Film Die to Pull-Roll

Predictions Vs. Expt : Film Thickness



- Two regimes were observed – one for the lower DR's (**dotted** line) for which $t \sim DR^{-0.5}$ and the other for the higher DR's (**solid** lines) for which $t \sim DR^{-1}$.
- Planar stretching conditions with a constant central film thickness are reached only for high DR conditions.

ALE Predictions

	HDPE		*LLDPE*	
DR	*Predicted Thickness*	*Expt Thickness*	*Predicted Thickness*	*Expt Thickness*
4.35	0.11460	0.08014	0.10320	0.09874
8.7	0.06150	0.06202	0.05340	0.06401
17.39	0.03226	0.03394	0.02854	0.02682

Predicted thickness values using the ALE technique (containing PTT viscoelastic constitutive equation) show good match with experimental results for HDPE and LLDPE materials.

Conclusions:

- Micro-scale extrusion film casting experiments were carried out on PE resins and the neck-in lengths and thickness values were measured.
- Branched PE (LDPE 170A) displayed extensional strain hardening and lower neck-in and lower film thickness; linear PE (LLDPE 2045G) did not display extensional strain hardening and consequently showed higher neck-in and higher film thickness.
- A steady-state neck-in model (Ito et al.) containing the KBKZ constitutive equation does not predict the draw ratio dependence of neck-in; whereas the experimental draw down ratio follows the Dobroth-Erwin model at high draw ratios.
- Predictions of ALE based FEM simulations containing the PTT constitutive eqn. showed good match with experimental values.

References:

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