List of Figures

Figure 1.1 Total flexible packaging market in India in 2010........................................3
Figure 1.2 Schematic of blown film extrusion process (www.varahii.com) .......5
Figure 1.3 Schematic of extrusion film casting (EFC) process 
          (www.eastman.com)...........................................................................................................5
Figure 1.4 Schematic of coextrusion coating process (www.extrusionist.com). 
          ..............................................................................................................................................6
Figure 1.5 Schematic of EFC process and associated defects...............................7
Figure 1.6 Schematic of film tentering process.................................................................8
Figure 1.7 Schematic of draw resonance instability in EFC process.........................9
Figure 1.8 Molecular structures for linear and branched PE's; (a) linear with 
          no branches, (b) linear with short branches, (c) linear with short 
          branches and sparse long branches and (d) branched structure with 
          both short and long branches. ..............................................................................................12
Figure 1.9 Linking polymer processing with macromolecular structure via 
          rheology.....................................................................................................................................15
Figure 2.1 The Rouse Model. ...............................................................................................20
Figure 2.2 A snake pit.............................................................................................................23
Figure 2.3 Reptation of a long and linearly entangled polymer chain 
          (http://home.sandiego.edu/~randerson)...............................................................25
Figure 2.4 Steps involved in reptation of entangled polymer chains 40 ...............25
Figure 2.5 Blob model of reptation.....................................................................................26
Figure 2.6 Mechanisms available for stress relaxation for linear entangled 
          polymer chain: (a) reptation, (b) constraint release, and (c) retraction.32
Figure 2.7 Tube model predictions for a 3-arm star polymer. .................................36
Figure 2.8 The structure of a pom-pom polymer with a backbone and 2q 
          dangling arms, with q=3, under various degrees of stretch ε.........................37
Figure 2.9 Schematic of the EFC process and associated flow kinematics......48
Figure 3.1 Classification of C-atoms on a branched PE chain.........................70
Figure 3.2 (a) 13C HT-NMR spectrum and (b) corresponding DEPT spectrum 
          for LDPE 170A obtained at 135°C .............................................................72
Figure 3.3 Principal of operation of a GPC.................................................................74
Figure 3.4 Malvern-Viscotek HT-GPC system with (A) semi-automated sample 
          preparation (SASP) and injection unit; (B) columns and detectors in 
          enclosed high-temperature oven; and (C) isocratic pumps. ..........................78
Figure 3.5 Molecular weight distribution (MWD) for the different PE's 
          characterized by HT-GPC technique..........................................................80
Figure 3.6 Plot of Intrinsic viscosity (IV) versus Log Mol. wt. for the four PEs. 
          ..............................................................................................................................................81
Figure 3.7 (a) Schematic representation 136 of rheometry with sample placed 
          between two parallel plates; (b) Schematic response to oscillatory shear 
          deformation for various materials.................................................................85
Figure 3.8 Dynamic amplitude sweep at 210°C and 50 rad/s for the PE resins. 
          ..............................................................................................................................................87
Figure 3.9 SAOS mastercurves, steady shear, and capillary rheology data for 
          the four PE resins at 190°C.........................................................................................91
Figure 3.10 Relaxation spectra of Maxwell parameters for the PE resins at 190°C

Figure 3.11 Viscoelastic creep: Applied Stress and evolved strain as a function of time (www.wikipedia.com).

Figure 3.12 Creep data at 190°C at 100 Pa applied stress for the PE resins.

Figure 3.13 SER fixture for extensional measurements (adapted from SER website (www.xinst.com)).

Figure 3.14 Transient rheology data for the PE resins at 150°C. Symbols: expt. data and lines: model fits. Open symbols: ext. data and closed symbols: shear start-up data. (Circles: 0.1 s-1; Triangles: 0.3 s-1; Squares: 1 s-1; Inverted triangles: 3 s-1; and Diamonds: 10 s-1; Dashed and solid lines are model predictions for step-shear and uniaxial extension).

Figure 4.1 Schematic of Rheomex 252 SSE.

Figure 4.2 Schematic of ThermoHaake coat-hanger cast film die of 100 mm width.

Figure 4.3 EFC process set-up inside a make-shift dark-room.

Figure 4.4 Close-up of necking of molten polymer film between the die-exit and chill-rolls.

Figure 4.5 Online stress birefringence set-up in EFC.

Figure 4.6 Placement of tracer particles on surface of molten PE film.

Figure 4.7 Representative plots for experimental (a and b). centerline velocity,(c) necking, and (d). thickness profiles for selected PE resins at given TUL’s and DR’s.

Figure 4.8 A representative IR Thermographic image of a PE film.

Figure 4.9 Measured centerline surface temperature of a representative PE film at a fixed TUL and DR.

Figure 5.1 Schematic of EFC process with associated flow kinematics.

Figure 5.2 Boundary conditions in EFC: (a) Stress free BC and (b) Kinematic free surface BC.

Figure 6.1 Experimental normalized final film width as a function of draw ratio for the four PE resins at the TUL of 230 mm.

Figure 6.2 Comparison of Experimental Necking Profile of LDPE 170A and LLDPE 2045G for (a) TUL of 230 mm and (b) TUL of 90 mm.

Figure 6.3 Comparison of Expt. and Predicted Necking Profile for LDPE 170A and LLDPE 2045G at a fixed DR of 6 for (a) TUL=230 mm and (b) TUL=90 mm. HW corresponds to film half-width.

Figure 6.4 Experimental film width profile of LLDPE 2045G and HDPE DMDH6400 at DR of 6 for TUL of 230 mm.

Figure 6.5 Experimental normalized final film width as a function of DR for (a) LDPE 170A, (b) LLDPE 2045G at Different TUL’s, and (c) LDPE and LLDPE at TUL=230 mm. For figure 6.5(a and b): Squares: TUL=10 mm; Circles: TUL=90 mm; Inverted triangles: TUL=230 mm.

Figure 6.6 Experimental normalized final film thickness as a function of DR for (a) LDPE 170A, (b) LLDPE 2045G at Different TUL’s, and (c) LDPE and LLDPE at TUL=230 mm. For figure 6.6(a and b): Squares: TUL=10 mm; Circles: TUL=90 mm; Inverted triangles: TUL=230 mm.

Figure 6.7 Normalized final film width as a function of DR for LDPE 170A and LLDPE 2045G for Experimental Set#1 and Set#2.
Figure 6.8 Normalized final film thickness as a function of DR for LDPE 170A and LLDPE 2045G for Experimental Set#1 and Set#2................................. 158
Figure 6.9 Centerline velocity profiles from PTV experiments at two DR’s for (a) Experimental data for LLDPE; (b) Experimental data for LDPE and (c) Experimental data for LLDPE and LDPE ............................................. 161
Figure 6.10 Transverse velocity (V_y) as a function of X-span for LDPE (a and b) and LLDPE (c and d) at low DR of 4 and high DR of 17. ......................... 164
Figure 6.11 Transverse velocity (V_y) as a function along width (Y) direction at different axial locations for LDPE (a and b) and LLDPE (c and d) resins at low DR of 4 and high DR of 17. .................................................. 168
Figure 6.12 (a) Normalized experimental thickness profiles for LLDPE versus LDPE, and re-normalized experimental thickness profiles for (b) LLDPE and (c) LDPE films. ................................................................. 171
Figure 6.13 Normalized experimental centerline temperature (scaled in degrees Kelvin) profiles for (a) LLDPE, (b) LDPE polymers and (c) LLDPE versus LDPE ........................................................................ 174
Figure 6.14 Edge-beading in PE films: Avg. final film thickness as a function of DR for LDPE (a and b) and LLDPE (c and d) films at TUL of 90 mm and 10 mm. Solid line is D-E scaling for center thickness (t~DR^{-3}) while dashed line is D-E scaling for edge thickness (t~DR^{-0.5}) ......................... 176
Figure 6.15 Comparison of (a) Expt. and (b) Predicted Necking Profile of LDPE 170A and LLDPE 2045G for one representative TUL of 90 mm.. 179
Figure 6.16 Comparison of Expt. and Predicted Necking Profile for the LDPE 170A and LLDPE 2045G at a fixed DR of 6 for (a) TUL=230 mm and (b) TUL=90 mm................................................................. 180
Figure 6.17 Isothermal stress ratio \( \sigma_{yy}/\sigma_{xx} \) predictions as a function of normalized axial distance for LLDPE 2045G and LDPE 170A at (a) various DR’s at TUL=90 mm and (b) various TUL’s at DR=6............ 182
Figure 6.18 Isothermal Predictions: Extent of necking \( (L_0-L) \) plotted as a function of normalized axial distance for LLDPE 2045G and LDPE 170A at (a) various DR’s at TUL=90 mm and (b) various TUL’s at DR=6...... 183
Figure 6.19(a, b) Isothermal Predictions: Molecular stretch for slowest relaxing mode for (a) DR=2 and (b) DR=17 and, (c, d) the corresponding axial stresses along stretching direction for (c) DR=2 and (d) DR=17. (Filled circles: LDPE; Open triangles: LLDPE) ................................. 186
Figure 6.20 Normalized final film width (Expt. and Predictions) as a function of DR for (a) LDPE 170A, (b) LLDPE 2045G at Different TUL’s, and (c) LDPE and LLDPE at TUL=230 mm. Symbols correspond to experimental data and lines correspond to predictions. For figure 6.21(a and b): Squares: TUL=10 mm; Circles: TUL=90 mm; Inverted triangles: TUL=230 mm................................................................. 188
Figure 6.21 Normalized final film thickness (Expt. and Predictions) as a function of DR for (a) LDPE 170A, (b) LLDPE 2045G at Different TUL’s, and (c) LDPE and LLDPE at TUL=230 mm. Symbols correspond to experimental data and lines correspond to predictions. For figure 6.22(a and b): Squares: TUL=10 mm; Circles: TUL=90 mm; Inverted triangles: TUL=230 mm................................................................. 189
Figure 6.22 Model predictions of the effect of DR on film necking for the m-LLDPE PL1840G and LLDPE 2045G at two DR's (a) low DR=4 and (b) high DR=17 at a TUL=10 mm.  

Figure 6.23 Effect of addition of branches on fast relaxing modes on the extent of necking (L_0-L) plotted as a function of normalized axial distance for m-LLDPE PL1840G and other related resins.  

Figure 6.24 Experimental and predicted (isothermal) necking profiles for LLDPE 2045G and HDPE DMDH6400 at a DR=6 and TUL=230 mm.  

Figure 6.25(a) Effect of polydispersity on extent of necking and (b) Effect of relaxation modes on extent of necking at a DR of 4 and TUL of 230 mm.  

Figure 6.26 Centerline velocity profiles at two DR's for (a) Experimental PTV data for LLDPE and LDPE; (b) Experimental and predicted data for LLDPE and (c) Experimental and predicted data for LDPE. Numbers in brackets are actual PTV measured DR's.  

Figure 6.27 Non-isothermal predictions of transverse velocity (V_y) as a function of width (or y) direction. (a) LLDPE at DR=4, (b) LDPE at DR=4, (c) LLDPE at DR=17, and (d) LDPE at DR=17.  

Figure 6.28 Stretch rates (\dot{\epsilon}_{yy}) in transverse (y or width) direction as a function of X-span for LDPE and LLDPE.  

Figure 6.29 Experimental and predicted normalized centerline temperature (scaled in K) profiles for (a) LLDPE, (b) LDPE resins. Numbers in brackets are actual PTV measured DR's.  

Figure 6.30 Normalized experimental and predicted necking profiles for (a) LLDPE versus LDPE, (b) LLDPE and (c) LDPE films. Numbers in brackets are actual PTV measured DR's.  

Figure 6.31 Normalized experimental and predicted thickness profiles for (a) LLDPE versus LDPE, (b) LLDPE and (c) LDPE films. Numbers in brackets are actual PTV measured DR's.  

Figure 6.32 Isothermal and non-isothermal predictions of stress ratio (\sigma_{yy}/\sigma_{xx}) plotted as a function of normalized axial-coordinate for LLDPE and LDPE.  

Figure 6.33 Effect of variation of total HTC on (a) Centerline Temperature profile, (b) Velocity profile, (c) Necking or width profile, and (d) Thickness profile.  

Figure 6.34 Isothermal and non-isothermal predictions of molecular stretch for slowest relaxing mode for LDPE and LLDPE at DR = 17.  

Figure 6.35 Effect of increasing LCB distribution on film properties at DR=25: (a) Centerline velocity profile; (b) Molecular stretch profile; (c) Film width profile; (d) Temperature profile.  

Figure 6.36 Effect of addition of LCB on fast relaxing modes on film properties at DR=25: (a) Centerline velocity profile; (b) Molecular stretch profile; (c) Film width profile; (d) Temperature profile.