APPENDIX A
Rheological and Thermophysical Properties of Polymers

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The characterization of polymer in terms of their thermal, rheological, and physical properties is vital for designing polymer processing equipment, for utilizing computer-aided design (CAD) and computer-aided manufacturing (CAM) software, for optimizing their operation, and for understanding and troubleshooting problems occurring during processing.

The thermophysical properties, such as glass transition, specific heat, melting point, and the crystallization temperature of virgin polymers are by-and-large available in the literature. However, the thermal conductivity or diffusivity, especially in the molten state, is not readily available, and values reported may differ due to experimental difficulties. The density of the polymer, or more generally, the pressure–volume–temperature (PVT) diagram, is also not readily available and the data are not easily convertible to simple analytical form. Thus, simplification or approximations have to be made to obtain a solution to the problem at hand.

The typical CAD software for injection molding may need the following properties to carry out a simulation:

- Rheological properties at three processing temperatures;
- Melting points and the heat of fusion;
- Crystallization temperature and the heat of crystallization at various cooling rates (or the ejection temperature of the molded part);
- Specific heat of the solid and melt (single value);
- Thermal conductivity and/or thermal diffusivity of the solid and melt (single value);
- Density of the solid and melt (single value) or the complete PVT diagram.

For the CAD software of the extrusion processes, in addition to these properties, the following are required:

Principles of Polymer Processing, Second Edition, by Zehev Tadmor and Costas G. Gogos.
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- Bulk density as a function of pressure and temperature;
- Friction coefficient at the polymer/metallic equipment surface interfaces.

The rheological properties of the polymers reported in Table A.1 were measured with a capillary die with diameter of 0.030 in or 0.050 in, and with *L*/*D* from 33 to 40. At processing temperatures, the effect of the entrance pressure could be neglected. The shear-rate dependence of viscosity is obtained by applying the Rabinowitsch correction.

The thermal properties of the polymers reported in Table A.2 and Table A.3 were obtained by using a Perkin-Elmer Differential Scanning Calorimeter Model DSC-7 using a heating rate of 20°C/min. The specific heat was obtained using a heating rate of 10°C/min. For semicrystalline material, the heat of fusion was obtained from the measured specific heat curves. The crystallization temperature was obtained at 20°C/min cooling rate.

The density of the polymer at 25°C was obtained by using a molded disk, 0.125 in thick and 2 in in diameter. The melt density at processing temperature was obtained with an Instron Capillary Rheometer with plugged exit. The isothermal compaction at melt-processing temperature was conducted at a plunger speed of 0.05 in/min with attainable pressures up to 25,000 psi.

The thermal conductivity was obtained with a miniaturized hot plate device,[1] using symmetrical heat flow. The apparatus can be heated to above the melt-processing temperature.

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[1] M. R. Kamal, V. Tan, and F. Kashani, "The Thermal Conductivity and Diffusivity of Polyethylene Solids and Melts," *Adv. Polym. Technol.*, **3**, pp. 89–98 (1983).

TABLE A.1 Parameters of the Power Law, Carreau, and Cross Rheological Models[a] for Commercial Polymers

		Power Law Model			Carreau Model				Cross Model			
Polymer, Commercial Designation, Manufacturer	Temperature (K)	Shear rate range (s^{-1})	m $\left(\frac{N\cdot s^n}{m^2}\right)$	n	Shear rate range (s^{-1})	n	λ (s)	η_0 $\left(\frac{N\cdot s}{m^2}\right)$	Shear rate range (s^{-1})	n	τ^* $\left(\frac{N}{m^2}\right)$	η_0 $\left(\frac{N\cdot s}{m^2}\right)$
Acrylonitrile butadiene styrene (ABS), AM-1000, Borg-Warner/GE Plasics[@]	443	100–5500	1.2×10^5	0.25	100–2000	0.29	0.82	8.0×10^4	–	–	–	–
	463	100–6000	6.3×10^4	0.25	100–3000	0.26	0.73	4.4×10^4	–	–	–	–
	483	100–7000	3.9×10^4	0.25	40–4000	0.25	0.57	2.6×10^4	–	–	–	–
ABS, Cycolac KJW, GE Plastics	493	300–14000	4.2×10^4	0.25	10–700	0.44	0.092	3.4×10^3	10–14000	1.77	1.2×10^5	3.6×10^3
	513	300–14000	2.3×10^4	0.30	10–700	0.45	0.1349	2.8×10^3	10–14000	1.73	6.6×10^4	2.9×10^3
	533	300–14000	1.4×10^4	0.32	10–700	0.44	0.1252	2.0×10^3	10–14000	1.70	4.3×10^4	2.3×10^3
Ethylene ethyl acrylate, DPDA-6169, Union Carbide/DOW[@]	443	100–6000	1.2×10^4	0.38	80–6000	0.42	0.40	5.4×10^3	–	–	–	–
	463	100–4000	6.9×10^3	0.43	10–3000	0.58	1.08	3.5×10^3	–	–	–	–
	483	100–6000	3.8×10^3	0.48	40–1000	0.50	0.51	2.3×10^3	–	–	–	–
Nylon, Capron 8200, Allied Chemical/Honeywell[@]	498	100–2500	2.6×10^3	0.63	100–2000	0.63	0.27	1.6×10^3	–	–	–	–
	503	100–2000	2.0×10^3	0.66	100–2000	0.65	0.32	1.3×10^3	–	–	–	–
	508	100–2300	1.8×10^3	0.66	100–2000	0.68	0.36	1.1×10^3	–	–	–	–
Nylon 6, Nylon 8202, BASF	508	700–3000	1.2×10^4	0.46	3–3000	0.49	0.0049	6.2×10^2	3–3000	1.86	5.0×10^5	6.5×10^2
	518	700–3000	7.1×10^3	0.50	3–3000	0.59	0.0093	5.4×10^2	3–3000	1.73	3.3×10^5	5.8×10^2
	528	700–3000	7.5×10^3	0.48	3–3000	0.55	0.0053	4.3×10^2	3–3000	1.82	3.9×10^5	4.5×10^2
Nylon 6 (Amorphous), Zytel 330, DuPont	503	300–750	8.2×10^4	0.33	3–750	0.46	0.026	5.1×10^3	–	–	–	–
	518	300–1500	4.2×10^4	0.39	3–1500	0.44	0.013	2.7×10^3	–	–	–	–
	533	300–3000	2.9×10^4	0.40	3–3000	0.41	0.0085	1.7×10^3	–	–	–	–

(*Continued*)

TABLE A.1 (*Continued*)

Polymer, Commercial Designation, Manufacturer	Temperature (K)	Power Law Model			Carreau Model				Cross Model			
		Shear rate range (s^{-1})	m $\left(\frac{N \cdot s^n}{m^2}\right)$	n	Shear rate range (s^{-1})	n	λ (s)	η_0 $\left(\frac{N \cdot s}{m^2}\right)$	Shear rate range (s^{-1})	n	τ^* $\left(\frac{N}{m^2}\right)$	η_0 $\left(\frac{N \cdot s}{m^2}\right)$
Nylon 6	553	100–300	9.6×10^4	0.36	3–300	0.42	0.054	1.3×10^4	–	–	–	–
(Amorphous),	573	300–1500	6.3×10^4	0.34	3–1500	0.36	0.020	4.5×10^3	–	–	–	–
Trogamid T-5000	593	300–3000	7.7×10^3	0.54	3–3000	0.48	0.0071	9.2×10^2	–	–	–	–
Degussa												
Nylon 66 + 33%	553	71–14164	3.5×10^3	0.53	–	–	–	–	–	–	–	–
Glass fiber, N 1503–2	563	71–14164	2.8×10^3	0.53	–	–	–	–	–	–	–	–
	573	71–14164	2.3×10^3	0.52	–	–	–	–	–	–	–	–
Polyblutene-1 (PB-1),	423	200–3000	2.4×10^3	0.46	3–3000	0.50	0.0446	3.9×10^2	3–3000	1.62	2.0×10^4	5.0×10^2
DP0800, Shell	443	200–3000	1.1×10^3	0.53	3–3000	0.58	0.0584	2.3×10^2	3–3000	1.55	1.1×10^4	3.0×10^2
	463	200–3000	3.4×10^2	0.63	3–3000	0.67	0.0961	1.2×10^2	3–3000	1.44	3.6×10^3	1.8×10^2
Polybutylene	513	700–14000	1.0×10^3	0.69	30–14000	0.71	0.0091	2.2×10^2	30–14000	1.44	1.3×10^5	3.0×10^2
terephthalate (PBT),	598	700–14000	7.9×10^2	0.68	30–14000	0.70	0.0084	1.6×10^2	30–14000	1.46	1.0×10^5	2.1×10^2
2000, Ticona	608	700–14000	4.3×10^2	0.71	30–14000	0.73	0.0152	1.2×10^2	30–14000	1.38	2.5×10^4	1.8×10^2
PBT with 30% GF,	523	10–14000	2.2×10^4	0.43	–	–	–	–	–	–	–	–
Vandar 4662 Z,	538	10–14000	1.2×10^4	0.42	–	–	–	–	–	–	–	–
Ticona	553	10–14000	6.5×10^3	0.40	–	–	–	–	–	–	–	–
Polycarbonate (PC),	553	100–1000	8.4×10^3	0.64	0.01–3000	0.26	0.002	1.5×10^3	–	–	–	–
Allied Chemical/	573	100–1000	4.3×10^3	0.67	0.01–2000	0.26	0.002	8.0×10^2	–	–	–	–
Honeywell@	593	100–1000	1.1×10^3	0.80	0.01–2500	0.53	0.002	4.2×10^2	–	–	–	–

PC, Lexan 141, GE Plastics	573	1000–3000	2.3×10^4	0.43	3–3000	0.26	0.0009	5.1×10^2	3–3000	2.40	1.4×10^6	5.2×10^2
	593	1000–3000	5.6×10^3	0.56	3–3000	– 1.39	0.0002	2.6×10^2	3–3000	3.08	1.1×10^6	2.6×10^2
	613	1000–3000	9.2×10^2	0.74	3–3000	0.63	0.0007	1.6×10^2	3–3000	2.35	9.9×10^5	1.6×10^2
High density polyethylene (HDPE), Alathon 7040, DuPont	453	100–1000	6.2×10^3	0.56	100–1200	0.54	0.07	2.1×10^3	–	–	–	–
	473	100–1000	4.7×10^3	0.59	100–1200	0.50	0.08	1.5×10^3	–	–	–	–
	493	100–1000	3.7×10^3	0.61	180–1400	0.58	0.05	1.2×10^3	–	–	–	–
HDPE (MI = 0.7), Marlex, Philips/Chevron	472	300–14000	4.1×10^4	0.27	10–14000	0.30	0.0259	2.4×10^3	10–14000	1.76	1.3×10^5	3.5×10^3
	550	300–14000	2.6×10^4	0.32	10–14000	0.34	0.0292	2.0×10^3	10–14000	1.72	9.7×10^4	3.1×10^3
	525	300–14000	1.8×10^4	0.35	10–14000	0.38	0.0361	1.8×10^3	10–14000	1.68	6.7×10^4	2.9×10^3
HDPE (MI = 10), Marlex, Philips/Chevron	453	100–1500	7.2×10^3	0.51	2–1500	0.54	0.0688	1.7×10^3	–	–	–	–
	463	100–1500	3.3×10^3	0.60	2–1500	0.62	0.0437	8.9×10^2	–	–	–	–
	473	100–1500	2.5×10^3	0.63	2–1500	0.63	0.0311	7.0×10^2	2–1500	1.63	1.3×10^5	7.8×10^2
HDPE (MI > 10), Alathon H-5618, DuPont	473	700–14000	8.0×10^3	0.41	10–14000	0.44	0.0061	3.6×10^2	10–14000	1.70	1.4×10^5	4.4×10^2
	507	700–14000	3.4×10^3	0.49	10–14000	0.52	0.0086	2.7×10^2	10–14000	1.61	8.0×10^4	3.5×10^2
	533	700–14000	2.3×10^3	0.53	10–14000	0.56	0.0078	2.0×10^2	10–14000	1.59	7.7×10^4	2.5×10^2
Low density polyethylene (LDPE), Alathon 1540, DuPont$^@$	433	100–4000	9.4×10^3	0.41	80–1000	0.42	0.59	6.3×10^3	–	–	–	–
	453	100–6500	5.2×10^3	0.46	100–7000	0.47	0.47	3.2×10^3	–	–	–	–
	473	100–6000	4.3×10^3	0.47	100–1000	0.48	0.21	1.7×10^3	–	–	–	–
LDPE (MI = 0.2), 132, DOW	453	3–3000	2.6×10^4	0.34	–	–	–	–	–	–	–	–
	473	3–3000	1.9×10^4	0.37	–	–	–	–	–	–	–	–
	493	3–3000	1.5×10^4	0.37	–	–	–	–	–	–	–	–
LDPE (MI = 2.0), 640, DOW	453	300–3000	2.1×10^4	0.35	3–3000	0.39	0.1822	5.9×10^3	–	–	–	–
	473	300–3000	1.6×10^4	0.37	3–3000	0.42	0.1222	3.3×10^3	–	–	–	–
	493	300–3000	9.9×10^3	0.42	3–3000	0.45	0.1026	2.2×10^3	–	–	–	–

(*Continued*)

TABLE A.1 (*Continued*)

		Power Law Model			Carreau Model				Cross Model			
Polymer, Commercial Designation, Manufacturer	Temperature (K)	Shear rate range (s^{-1})	m $\left(\frac{N \cdot s^n}{m^2}\right)$	n	Shear rate range (s^{-1})	n	λ (s)	η_0 $\left(\frac{N \cdot s}{m^2}\right)$	Shear rate range (s^{-1})	n	τ^* $\left(\frac{N}{m^2}\right)$	η_0 $\left(\frac{N \cdot s}{m^2}\right)$
LDPE (MI = 50),	423	300–3000	4.4×10^3	0.48	3–3000	0.51	0.0253	5.6×10^2	3–3000	1.64	6.3×10^4	6.8×10^2
1409, Chevron/Philips	448	300–3000	1.9×10^3	0.55	3–3000	0.57	0.0143	2.6×10^2	3–3000	1.68	8.2×10^4	2.9×10^2
	473	300–3000	1.0×10^3	0.59	3–3000	0.61	0.0108	1.5×10^2	3–3000	1.67	8.2×10^4	1.7×10^2
Linear low density	453	400–1500	1.3×10^4	0.44	2–1500	0.53	0.0316	1.3×10^3	–	–	–	–
polyethylene	463	400–1500	6.7×10^4	0.20	–	–	–	–	–	–	–	–
(LLDPE) (MI = 6),	473	400–1500	8.4×10^3	0.48	2–1500	0.57	0.0372	1.1×10^3	–	–	–	–
Dowlex 2035, DOW												
LLDPE (MI = 50),	423	300–3000	2.7×10^3	0.57	3–3000	0.55	0.0062	3.1×10^2	–	–	–	–
Dowlex 2500, DOW	448	300–3000	1.1×10^3	0.65	3–3000	0.61	0.0045	1.8×10^2	–	–	–	–
	473	300–3000	5.7×10^2	0.70	3–3000	0.67	0.0047	1.2×10^2	–	–	–	–
Polymethyl	493	100–6000	8.8×10^4	0.19	100–4000	0.19	0.09	1.3×10^4	–	–	–	–
methacrylate (PMMA),	513	100–6000	4.3×10^4	0.25	100–4000	0.25	0.07	6.0×10^3	–	–	–	–
Lucite 147, DuPont@	533	100–7000	2.6×10^4	0.27	100–4000	0.36	0.11	2.9×10^3	–	–	–	–
PMMA, V811–100,	473	100–1500	1.7×10^5	0.25	3–1500	0.30	0.199	3.9×10^4	–	–	–	–
Rohm & Haas	493	100–3000	5.8×10^4	0.31	3–3000	0.43	0.4313	1.0×10^4	–	–	–	–
	513	100–3000	2.3×10^4	0.37	3–3000	0.42	0.4170	4.8×10^3	–	–	–	–
Polyoxymethylene	473	1000–14000	1.5×10^4	0.37	30–14000	0.38	0.002	2.9×10^2	30–14000	1.84	3.6×10^5	3.2×10^2
(POM) (Acetal),	483	1000–14000	9.7×10^3	0.40	30–14000	0.40	0.002	2.3×10^2	–	–	–	–
Delrin 507, DuPont	493	1000–14000	7.5×10^3	0.42	30–14000	0.40	0.0016	1.9×10^2	30–14000	1.85	3.3×10^5	2.1×10^2

POM (Copolymer), Celcon U10–01, Ticona	453	3–3000	6.7×10^{3}	0.57	–	–	–	–	–	–	–	–
	468	3–3000	1.1×10^{4}	0.49	–	–	–	–	–	–	–	–
	483	75–3000	$1. 8 \times 10^{4}$	0.42	3–3000	0.45	0.1403	4.9×10^{3}	–	–	–	–
POM (Copolymer), Celcon MM3.5H, Ticona	453	300–1500	4.4×10^{3}	0.57	3–1500	0.66	0.0318	7.3×10^{2}	–	–	–	–
	468	300–1500	2.8×10^{3}	0.60	3–1500	0.68	0.021	4.9×10^{2}	3–1500	1.62	1.8×10^{5}	5.4×10^{2}
	483	300–1500	1.3×10^{3}	0.69	3–1500	0.72	0.0197	3.5×10^{2}	3–1500	1.56	1.7×10^{5}	4.0×10^{2}
Polyphenylene Sulfide (PPS), Fortron 0214B1, Ticona	583	1000–14000	2.4×10^{3}	0.59	140–14000	0.59	0.0016	1.8×10^{2}	140–14000	1.67	4.6×10^{5}	2.1×10^{2}
	598	1000–14000	1.1×10^{3}	0.66	140–14000	0.66	0.0017	1.3×10^{2}	140–14000	1.61	4.3×10^{5}	1.5×10^{2}
	603	1000–14000	5.4×10^{2}	0.72	140–14000	0.66	0.0007	8.0×10^{1}	140–14000	1.76	8.1×10^{5}	8.5×10^{1}
Polypropylene (PP), CD 460, Exxon Mobil Chemical@	453	100–4000	6.8×10^{3}	0.37	70–4000	0.38	0.49	4.2×10^{3}	–	–	–	–
	463	100–3500	4.9×10^{3}	0.41	70–4000	0.41	0.51	3.2×10^{3}	–	–	–	–
	473	100–4000	4.4×10^{3}	0.41	50–3000	0.41	0.40	2.5×10^{3}	–	–	–	–
PP, E612 ExxonMobil Chemical@	483	100–3000	3.2×10^{4}	0.25	100–3500	0.24	1.05	3.5×10^{4}	–	–	–	–
	513	50–3000	2.2×10^{4}	0.28	50–3500	0.27	0.81	2.0×10^{4}	–	–	–	–
PP (MFI = 1.4), -, Shell	463	3–3000	2.1×10^{4}	0.32	–	–	–	–	–	–	–	–
	483	3–3000	1.7×10^{4}	0.32	–	–	–	–	–	–	–	–
	503	3–3000	1.4×10^{4}	0.35	–	–	–	–	–	–	–	–
PP (MFI = 7.8) Shell	463	3–3000	6.9×10^{3}	0.41	–	–	–	–	–	–	–	–
	483	3–3000	4.9×10^{3}	0.44	–	–	–	–	–	–	–	–
	503	3–3000	3.6×10^{3}	0.47	–	–	–	–	–	–	–	–
PP (MFI = 53) Shell	463	300–3000	1.2×10^{3}	0.61	3–3000	0.45	0.0305	5.0×10^{2}	3–3000	1.69	3.7×10^{4}	6.2×10^{2}
	483	300–3000	6.7×10^{2}	0.67	3–3000	0.49	0.0222	3.0×10^{2}	3–3000	1.68	3.9×10^{4}	3.6×10^{2}
	503	300–3000	3.6×10^{2}	0.73	3–3000	0.50	0.0115	1.8×10^{2}	3–3000	1.75	5.7×10^{4}	2.0×10^{2}
PP-PE copolymer, 7523, Basell	463	10–1400	1.9×10^{4}	0.35	–	–	–	–	–	–	–	–
	483	10–14000	2.1×10^{4}	0.31	–	–	–	–	–	–	–	–
	503	10–14000	1.8×10^{4}	0.31	–	–	–	–	–	–	–	–
Polystyrene (PS), Dylene 8, ARCO/BP@	463	100–4500	4.5×10^{4}	0.22	30–6000	0.24	0.27	1.4×10^{5}	–	–	–	–
	483	100–4000	2.4×10^{4}	0.25	30–4000	0.27	0.32	9.2×10^{3}	–	–	–	–
	498	100–5000	$1. 6 \times 10^{4}$	0.28	30–4000	0.30	0.35	6.6×10^{3}	–	–	–	–

(*Continued*)

TABLE A.1 (*Continued*)

Polymer, Commercial Designation, Manufacturer	Temperature (K)	Power Law Model			Carreau Model				Cross Model			
		Shear rate range (s^{-1})	m $\left(\frac{N \cdot s^n}{m^2}\right)$	n	Shear rate range (s^{-1})	n	λ (s)	η_0 $\left(\frac{N \cdot s}{m^2}\right)$	Shear rate range (s^{-1})	n	τ^* $\left(\frac{N}{m^2}\right)$	η_0 $\left(\frac{N \cdot s}{m^2}\right)$
PS, Styron 615, DOW	453	100–3000	2.9×10^4	0.33	3–3000	0.35	0.2678	1.1×10^4	–	–	–	–
	473	100–3000	1.7×10^4	0.33	3–3000	0.35	0.1074	3.5×10^3	–	–	–	–
	493	100–3000	7.9×10^3	0.38	3–3000	0.40	0.0614	1.3×10^3	3–3000	1.69	3.6×10^4	1.8×10^3
PS, Styron 685, DOW	453	3–3000	4.8×10^4	0.30	–	–	–	–	–	–	–	–
	473	3–3000	3.1×10^4	0.28	–	–	–	–	–	–	–	–
	493	3–3000	1.5×10^4	0.34	–	–	–	–	–	–	–	–
High-impact polystyrene (HIPS), MC6800, Chevron/Philips	473	10–16000	1.7×10^4	0.32	–	–	–	–	–	–	–	–
	498	10–16000	9.6×10^3	0.34	–	–	–	–	–	–	–	–
	523	10–16000	5.5×10^3	0.38	–	–	–	–	–	–	–	–
HIPS, LX2400, Solutia@	443	100–7000	7.6×10^4	0.20	50–1000	0.26	6.77	2.1×10^5	–	–	–	–
	463	100–7000	4.6×10^4	0.21	50–1000	0.22	5.31	1.5×10^5	–	–	–	–
	483	100–7000	3.6×10^4	0.19	100–3000	0.16	2.57	1.1×10^5	–	–	–	–
Polyurethane (PU), TTFG80A	416	100–1400	1.9×10^5	0.21	10–1400	0.21	0.028	1.1×10^4	–	–	–	–
	438	300–7000	1.0×10^5	0.26	10–7000	0.28	0.0148	4.2×10^3	–	–	–	–
	466	1000–14000	1.3×10^4	0.41	10–14000	0.40	0.0031	4.6×10^2	10–14000	1.78	3.6×10^5	5.2×10^2
Polyvinyl chloride (PVC), Polyvin 9774	438	400–14000	3.5×10^4	0.23	10–14000	0.25	0.0393	2.6×10^3	10–14000	1.79	7.5×10^4	4.4×10^3
	453	400–14000	1.2×10^4	0.33	10–14000	0.36	0.0377	1.1×10^3	10–14000	1.69	3.7×10^4	1.8×10^3
	473	400–14000	3.5×10^3	0.44	10–14000	0.45	0.0149	3.1×10^2	10–14000	1.64	3.8×10^4	4.4×10^2
Styrene acrylonitrile (SAN), Lustran 31–1000, Solutia@	463	100–9000	9.0×10^4	0.21	100–8000	0.21	0.17	2.2×10^4	–	–	–	–
	493	100–8000	3.2×10^4	0.27	80–8000	0.28	0.18	9.0×10^3	–	–	–	–
	523	100–8000	1.1×10^4	0.35	100–5000	0.36	0.25	4.2×10^3	–	–	–	–

Styrene-butadiene-	463	400–16000	1.3×10^4	0.29	20–16000	0.30	0.0216	7.8×10^2	20–16000	1.74	4.3×10^4	1.3×10^3
styrene (SBS), 787,	508	400–16000	7.9×10^3	0.32	20–16000	0.32	0.0102	3.3×10^2	20–16000	1.75	4.7×10^4	4.5×10^2
Shell[@]	553	400–16000	3.7×10^3	0.38	20–16000	0.36	0.0061	1.6×10^2	20–16000	1.75	4.7×10^4	2.0×10^2
Polyethylene	553	1400–14000	7.4×10^3	0.48	70–14000	0.51	0.0028	3.2×10^2	70–14000	1.69	3.5×10^5	3.9×10^2
terephthalate (PET),	563	1400–14000	4.9×10^3	0.51	70–14000	0.51	0.0018	2.3×10^2	70–14000	1.75	4.4×10^5	2.6×10^2
7352, Amoco/BP,	573	3500–14000	4.1×10^3	0.51	70–14000	0.59	0.0021	1.6×10^2	70–14000	1.66	3.6×10^5	1.9×10^2
Thermoplastic	463	300–14000	1.2×10^4	0.41	10–14000	0.44	0.0185	9.7×10^2	10–14000	1.65	8.9×10^4	1.4×10^3
elastomer (TPE),	473	300–14000	8.7×10^3	0.43	10–14000	0.45	0.0159	7.6×10^2	10–14000	1.65	8.9×10^4	1.0×10^3
Riteflex, Ticona	483	300–14000	5.2×10^3	0.48	10–14000	0.51	0.0237	6.6×10^2	10–14000	1.59	5.3×10^4	9.4×10^2
Thermoplastic	473	100–5000	2.8×10^4	0.27	40–5000	0.28	1.62	3.6×10^4	–	–	–	–
olefin (TPO),	493	100–4000	1.8×10^4	0.30	70–2000	0.31	1.42	2.2×10^4	–	–	–	–
Vistaflex905 B,	513	100–3000	2.0×10^4	0.28	70–2000	0.31	0.72	1.4×10^4	–	–	–	–
ExxonMobil												
Chemical[@]												
Polyether sulphone	608	1400–7000	5.6×10^4	0.37	14–7000	0.48	0.0116	2.3×10^3	14–7000	1.66	4.8×10^5	2.9×10^3
(PES), Ultem 1010,	623	1400–14000	4.2×10^4	0.37	14–14000	0.45	0.0062	1.2×10^3	14–14000	1.70	4.9×10^5	1.4×10^3
GE Plastics	643	1400–14000	1.5×10^4	0.45	14–14000	0.51	0.0054	6.7×10^2	14–14000	1.65	3.7×10^5	8.0×10^2
PES, 3600G, ICI	603	7–750	1.5×10^3	0.88	7–750	0.85	0.050	1.1×10^3	–	–	–	–
	623	15–3000	1.2×10^3	0.80	15–3000	0.75	0.0218	6.3×10^2	15–3000	1.50	3.6×10^5	7.4×10^2
	643	15–3000	7.0×10^2	0.80	15–3000	0.79	0.0793	4.3×10^2	15–3000	1.29	9.5×10^3	8.0×10^2

[@] Data appeared in Appendix A of First Edition.

Power Law model:

$$\eta(\dot{\gamma}) = m\dot{\gamma}^{n-1}$$

Carreau model:

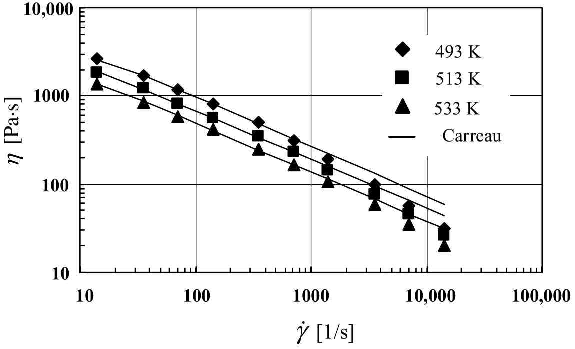
$$\frac{\eta(\dot{\gamma}) - \eta_\infty}{\eta_0 - \eta_\infty} = \frac{1}{[1 + (\lambda\dot{\gamma})^2]^{(1-n)/2}}$$

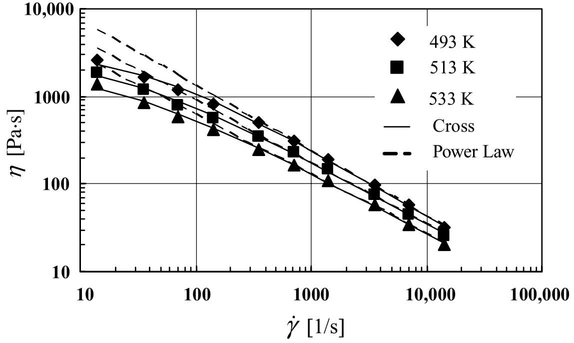
Parameters given with η_∞ set to zero

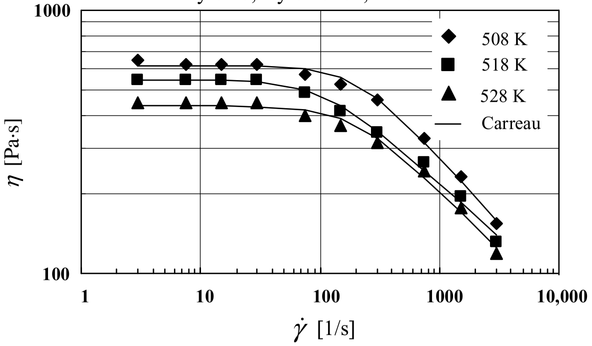
Cross model:

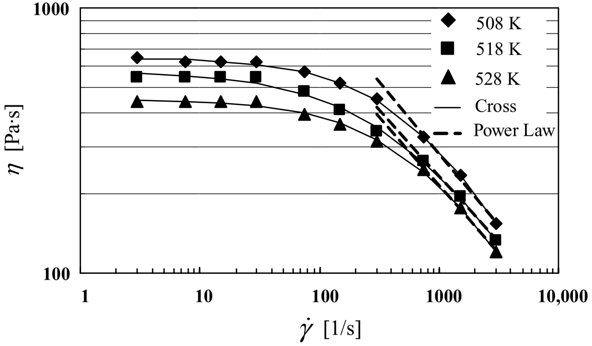
$$\eta(\dot{\gamma}, T, P) = \frac{\eta_0(T_1)}{1 + \left[\frac{\eta_0(T)}{\tau *}\dot{\gamma}\right]^{n-1}}$$

EXPERIMENTAL RESULTS AND POWER LAW, CARREAU, AND CROSS MODELS CURVE FITS

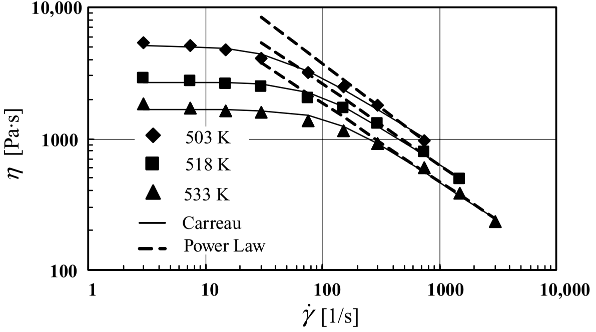

ABS, Cycolac KJW, GE Plastics


ABS, Cycolac KJW, GE Plastics

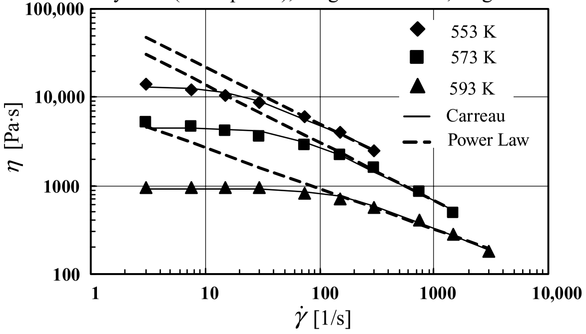

Nylon 6, Nylon 8202, BASF


Nylon 6, Nylon 8202, BASF

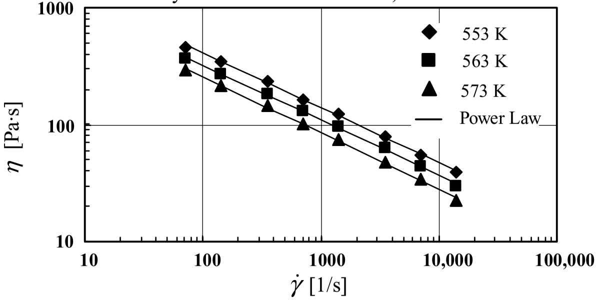
Nylon 6 (Amorphous), Zytel 330, Dupont

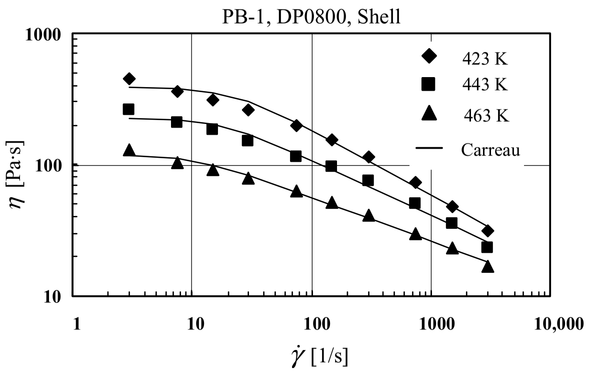


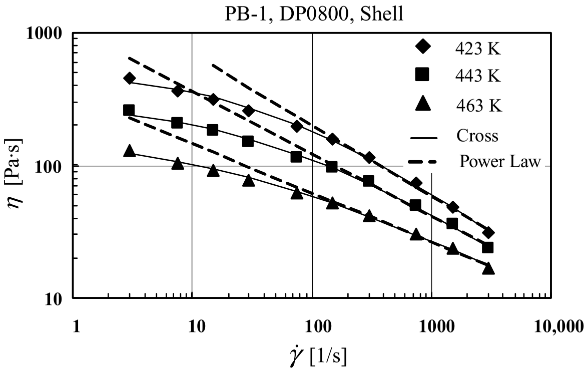
Nylon 6 (Amorphous), Trogamid T-5000, Degussa

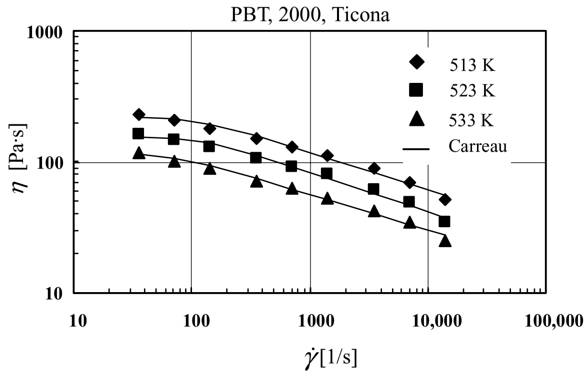


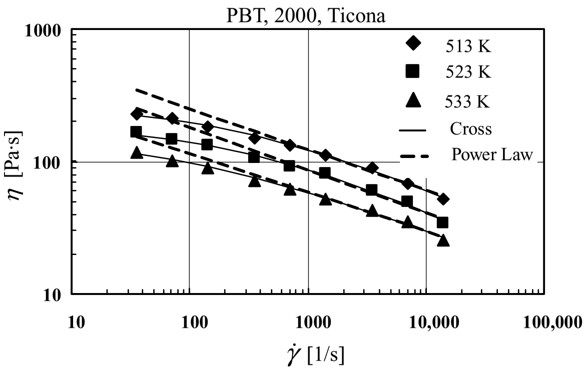
Nylon 66 +33% Glass fiber, N 1503-2

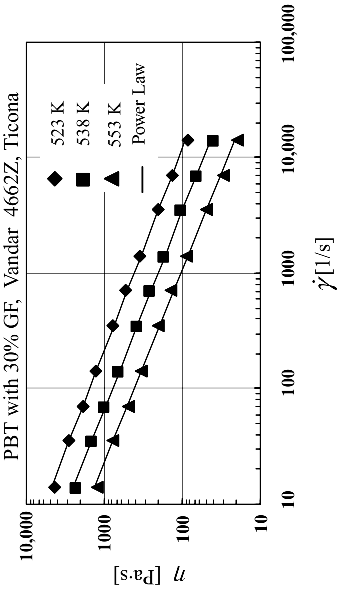


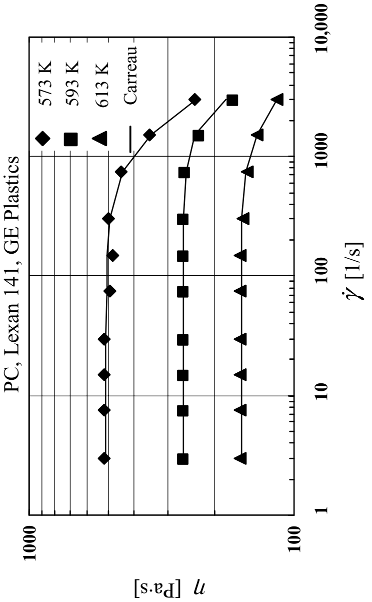

PB-1, DP0800, Shell

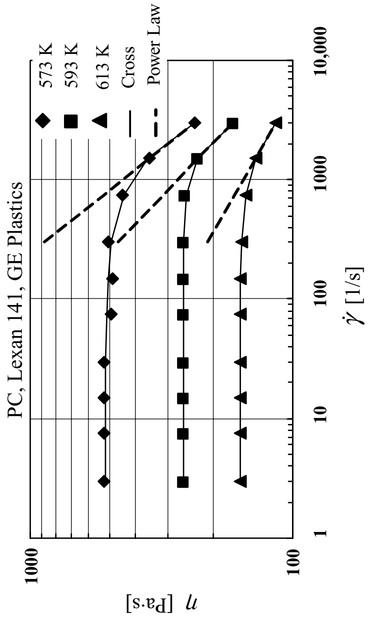

PB-1, DP0800, Shell

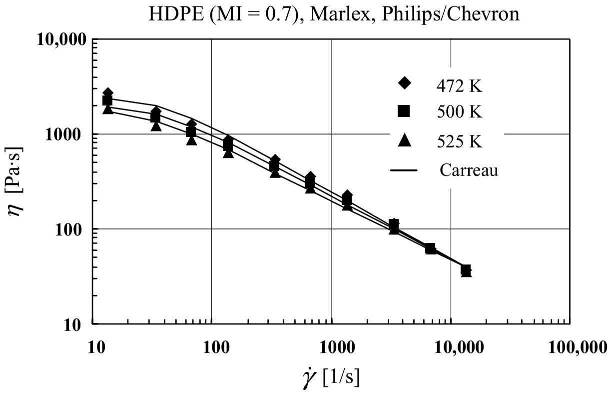

PBT, 2000, Ticona

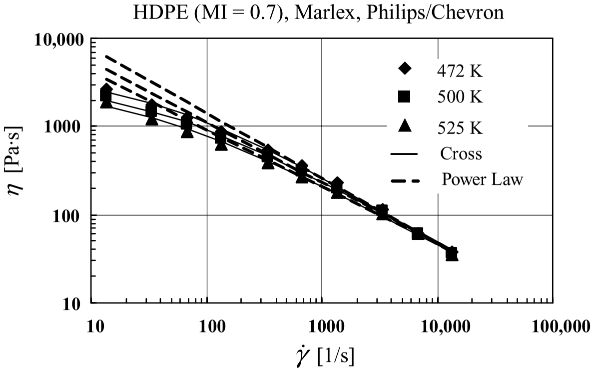

PBT, 2000, Ticona

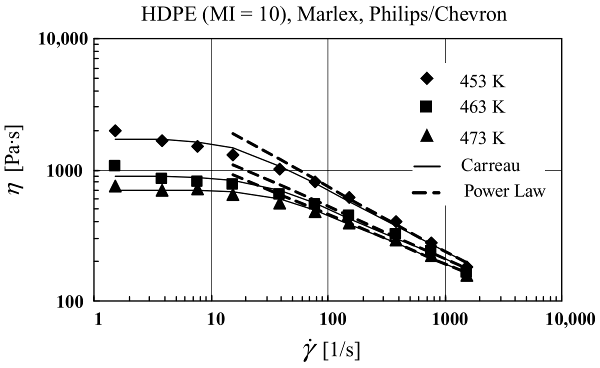

PBT with 30% GF, Vandar 4662Z, Ticona
523 K
538 K
553 K
Power Law
η [Pa·s]
10,000
1000
100
10
γ̇[1/s]
10
100
1000
10,000
100,000

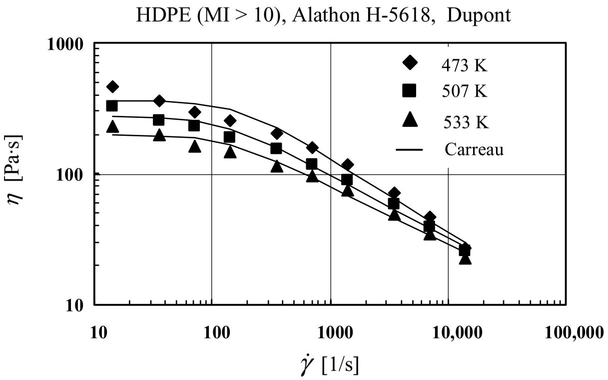

PC, Lexan 141, GE Plastics
573 K
593 K
613 K
Carreau
η [Pa·s]
1000
100
γ̇ [1/s]
1
10
100
1000
10,000

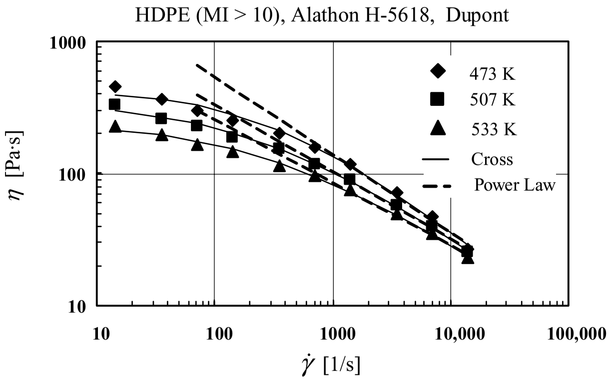

PC, Lexan 141, GE Plastics
573 K
593 K
613 K
Cross
Power Law
η [Pa·s]
1000
100
γ̇ [1/s]
1
10
100
1000
10,000

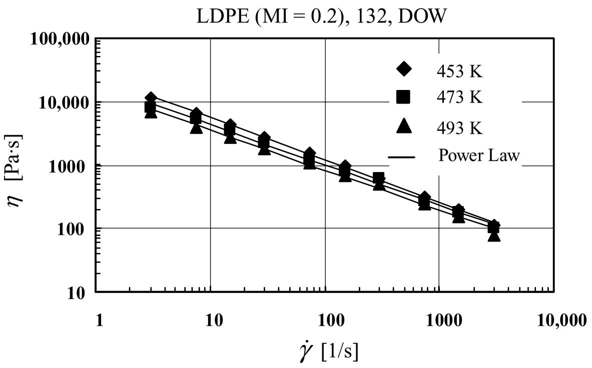

HDPE (MI = 0.7), Marlex, Philips/Chevron

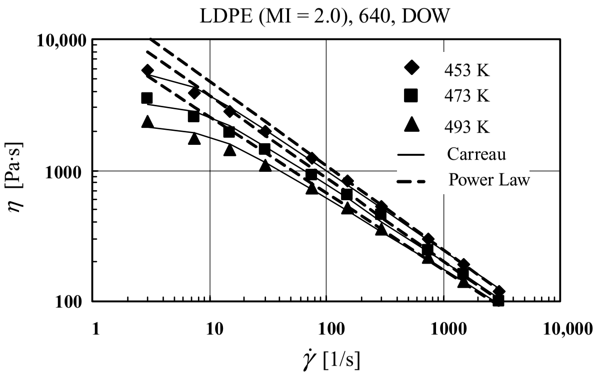

HDPE (MI = 0.7), Marlex, Philips/Chevron

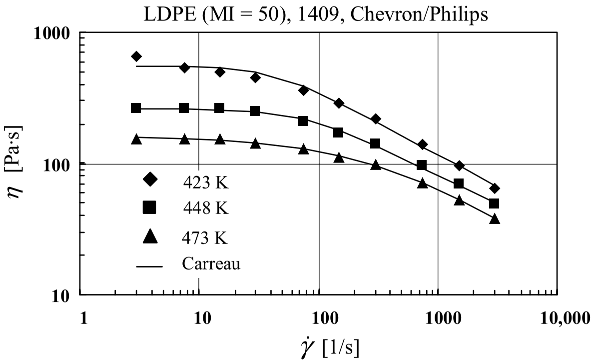

HDPE (MI = 10), Marlex, Philips/Chevron

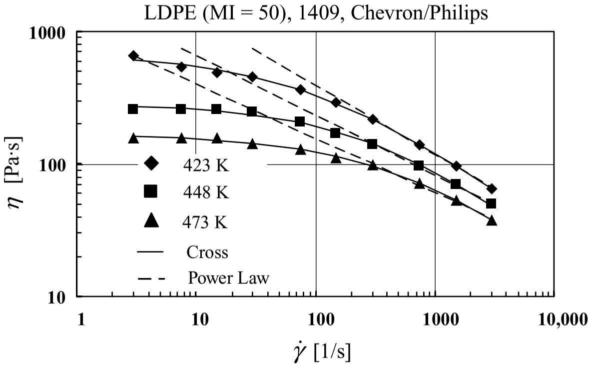

HDPE (MI > 10), Alathon H-5618, Dupont

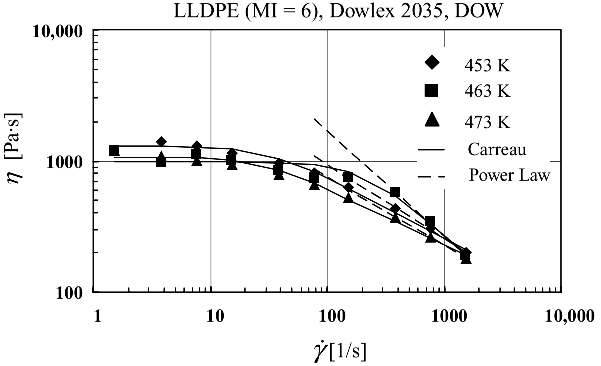

HDPE (MI > 10), Alathon H-5618, Dupont

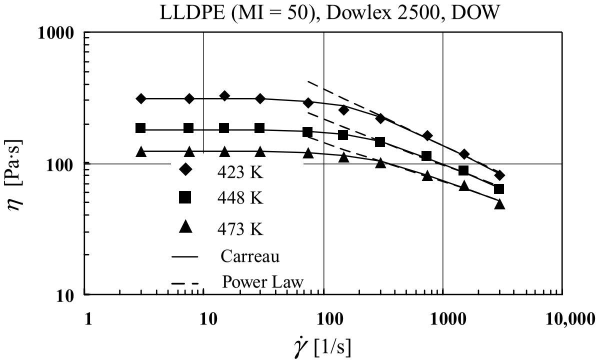

LDPE (MI = 0.2), 132, DOW

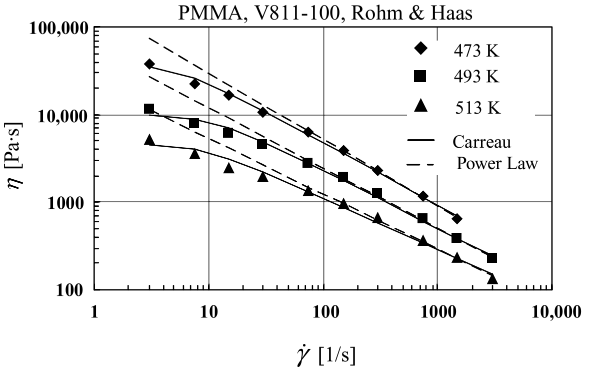

LDPE (MI = 2.0), 640, DOW

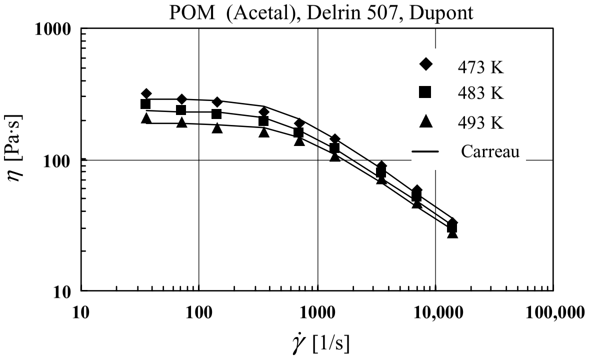

LDPE (MI = 50), 1409, Chevron/Philips
η [Pa·s]
1000
100
10
1
10
100
1000
10,000
$\dot{\gamma}$ [1/s]
423 K
448 K
473 K
Carreau

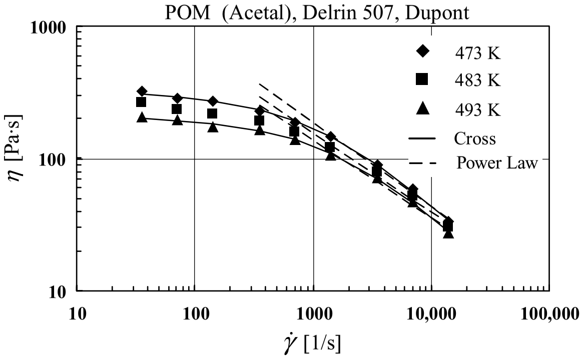

LDPE (MI = 50), 1409, Chevron/Philips
η [Pa·s]
1000
100
10
1
10
100
1000
10,000
$\dot{\gamma}$ [1/s]
423 K
448 K
473 K
Cross
Power Law

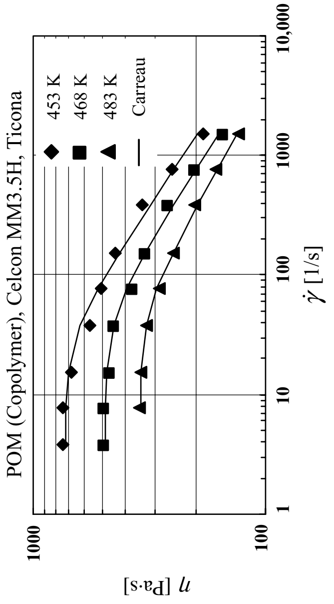

LLDPE (MI = 6), Dowlex 2035, DOW
η [Pa·s]
10,000
1000
100
1
10
100
1000
10,000
$\dot{\gamma}$[1/s]
453 K
463 K
473 K
Carreau
Power Law

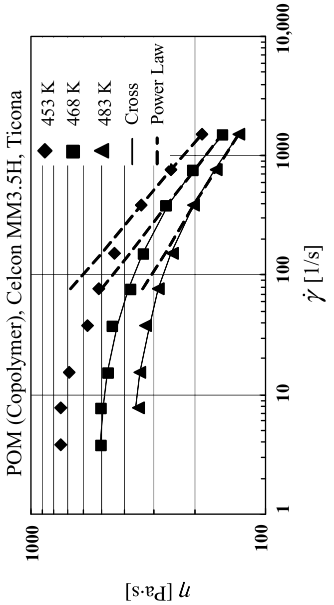

LLDPE (MI = 50), Dowlex 2500, DOW
η [Pa·s]
1000
100
10
1
10
100
1000
10,000
$\dot{\gamma}$ [1/s]
423 K
448 K
473 K
Carreau
Power Law

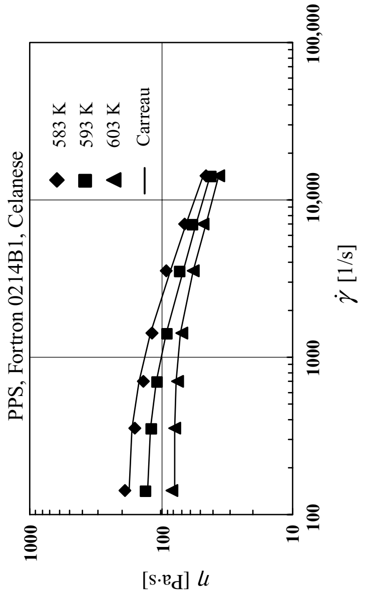

PMMA, V811-100, Rohm & Haas
473 K
493 K
513 K
Carreau
Power Law
η [Pa·s]
100,000
10,000
1000
100
1
10
100
1000
10,000
$\dot{\gamma}$ [1/s]

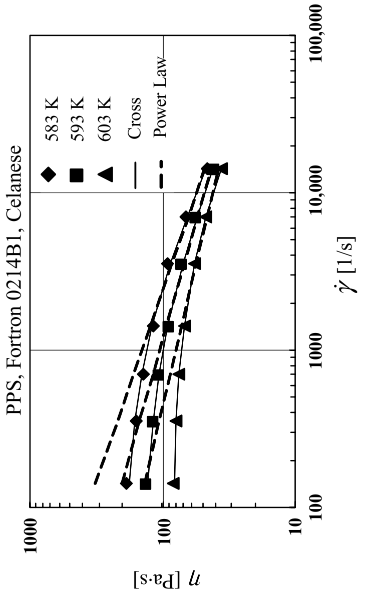

POM (Acetal), Delrin 507, Dupont
473 K
483 K
493 K
Carreau
η [Pa·s]
1000
100
10
10
100
1000
10,000
100,000
$\dot{\gamma}$ [1/s]

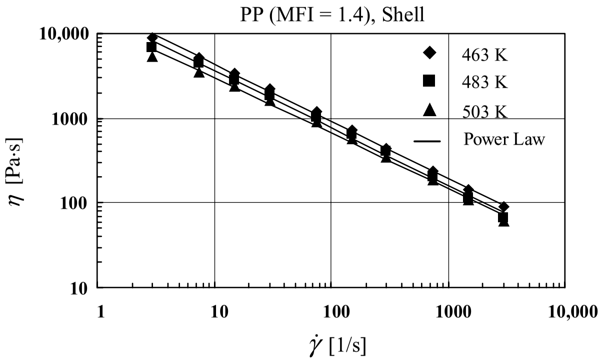

POM (Acetal), Delrin 507, Dupont
473 K
483 K
493 K
Cross
Power Law
η [Pa·s]
1000
100
10
10
100
1000
10,000
100,000
$\dot{\gamma}$ [1/s]

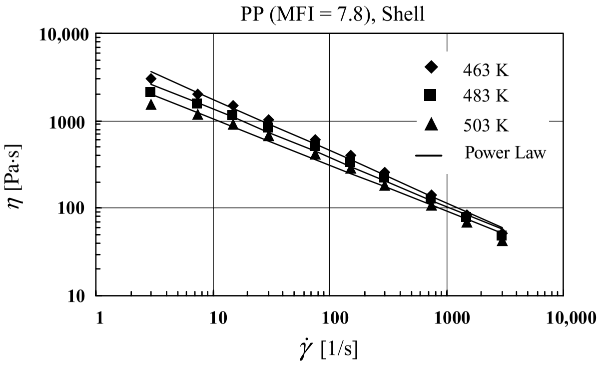

POM (Copolymer), Celcon MM3.5H, Ticona
453 K
468 K
483 K
Carreau
η [Pa·s]
$\dot{\gamma}$ [1/s]
1000
100
1
10
100
1000
10,000

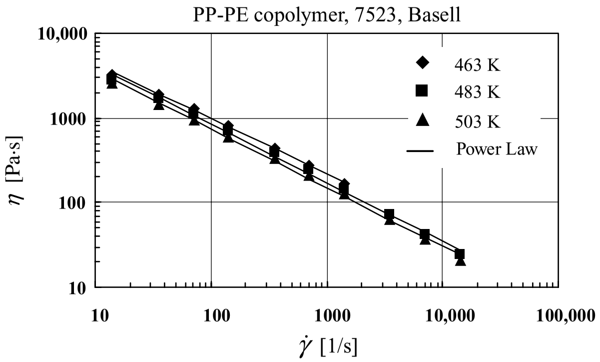

POM (Copolymer), Celcon MM3.5H, Ticona
453 K
468 K
483 K
Cross
Power Law
η [Pa·s]
$\dot{\gamma}$ [1/s]
1000
100
1
10
100
1000
10,000

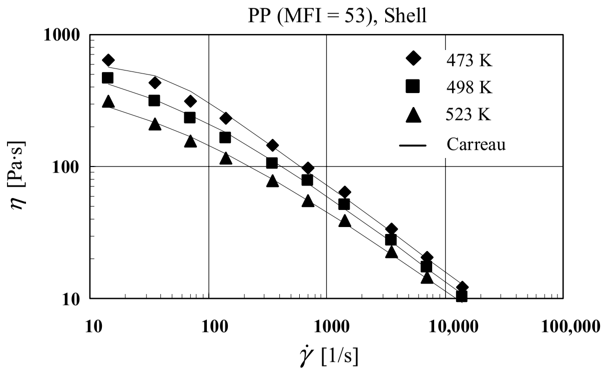

PPS, Fortron 0214B1, Celanese
583 K
593 K
603 K
Carreau
η [Pa·s]
$\dot{\gamma}$ [1/s]
1000
100
10
100
1000
10,000
100,000

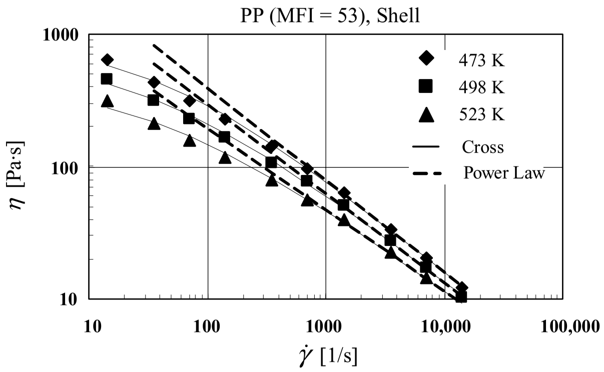

PPS, Fortron 0214B1, Celanese
583 K
593 K
603 K
Cross
Power Law
η [Pa·s]
$\dot{\gamma}$ [1/s]
1000
100
10
100
1000
10,000
100,000

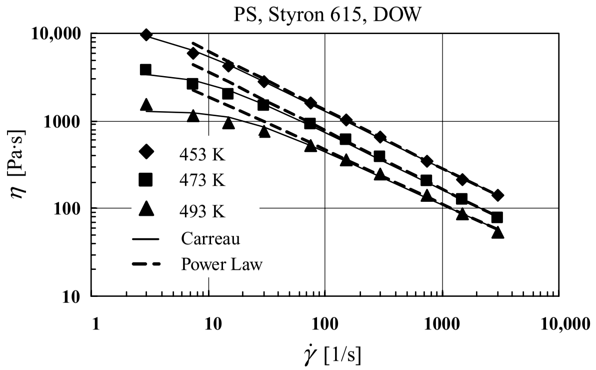

PP (MFI = 1.4), Shell
463 K
483 K
503 K
Power Law
η [Pa·s]
10,000
1000
100
10
1
10
100
1000
10,000
$\dot{\gamma}$ [1/s]

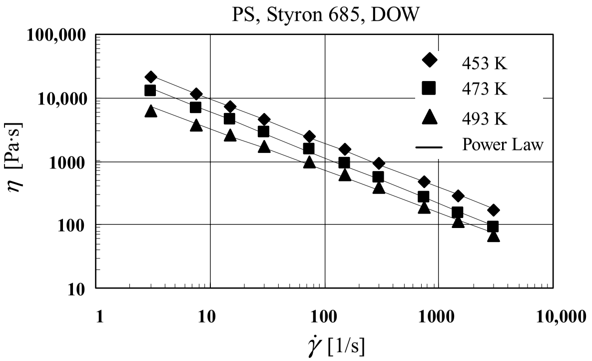

PP (MFI = 7.8), Shell
463 K
483 K
503 K
Power Law
η [Pa·s]
10,000
1000
100
10
1
10
100
1000
10,000
$\dot{\gamma}$ [1/s]


PP-PE copolymer, 7523, Basell
463 K
483 K
503 K
Power Law
η [Pa·s]
10,000
1000
100
10
10
100
1000
10,000
100,000
$\dot{\gamma}$ [1/s]

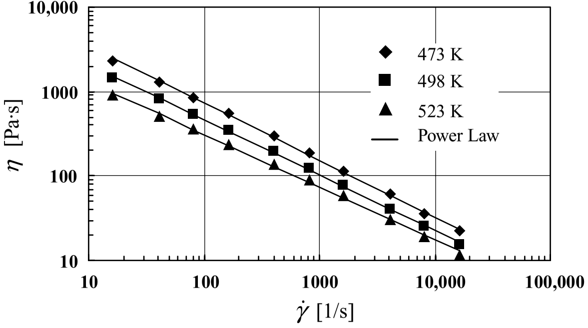

PP (MFI = 53), Shell


PP (MFI = 53), Shell

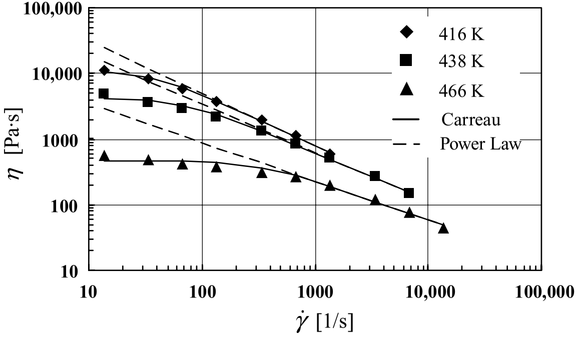

PS, Styron 615, DOW


PS, Styron 685, DOW

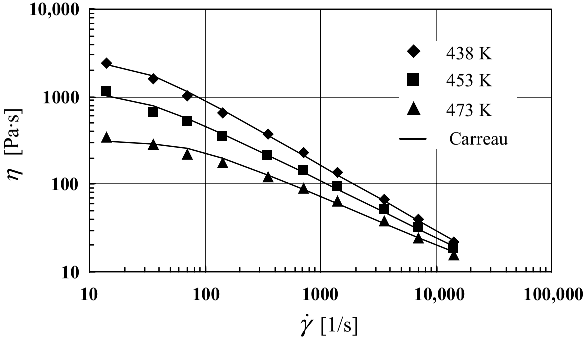
HIPS, MC6800, Chevron/Philips



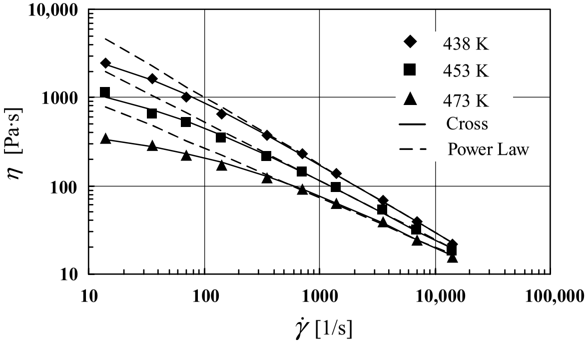
PU, TTFG80A

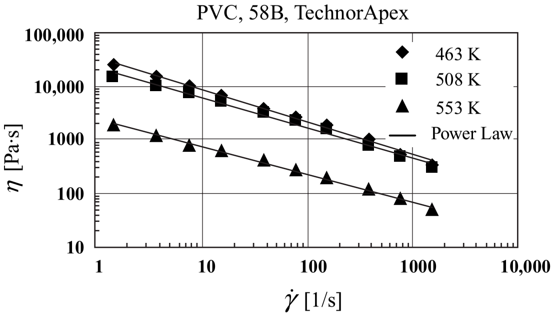


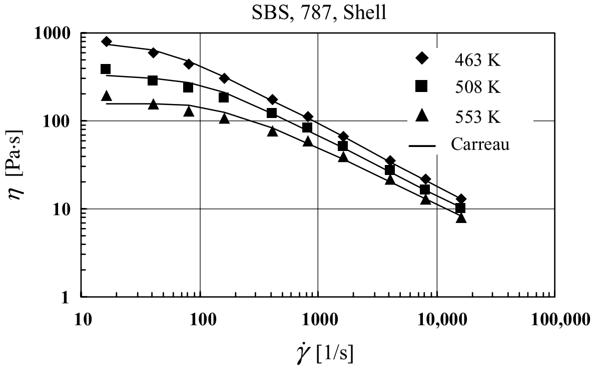
PVC, Polyvin 9774

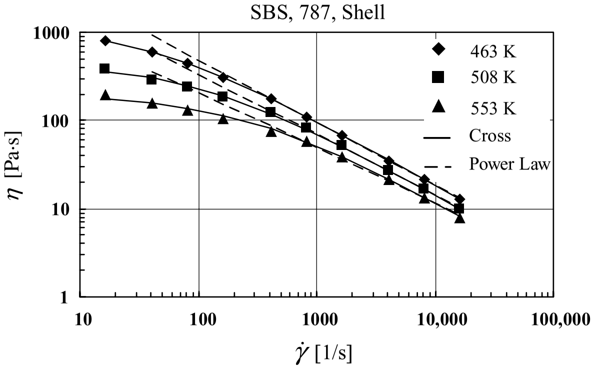


PVC, Polyvin 9774

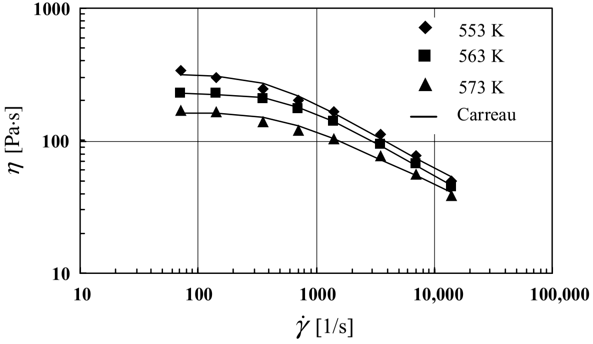



PVC, 58B, TechnorApex

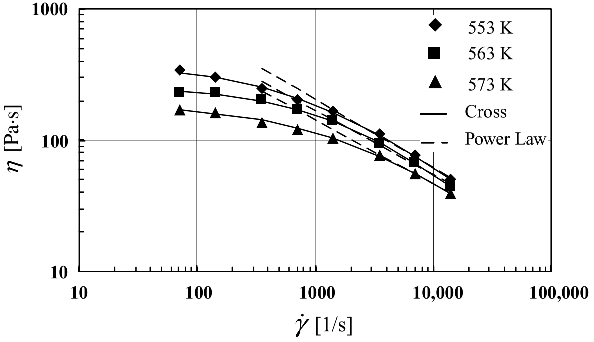

SBS, 787, Shell


SBS, 787, Shell

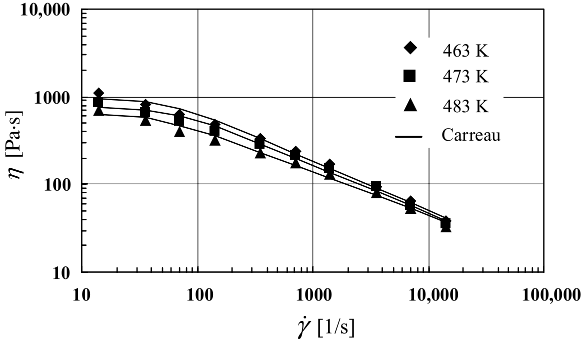
PET, 7352, Amoco/BP



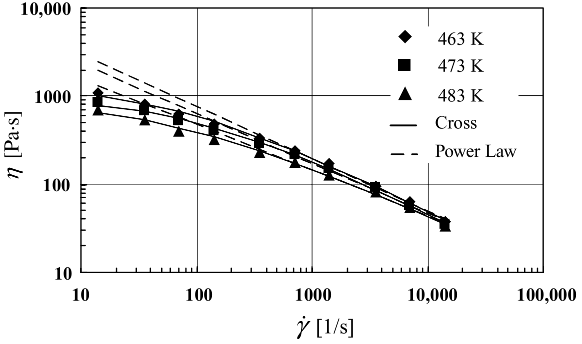
PET, 7352, Amoco/BP

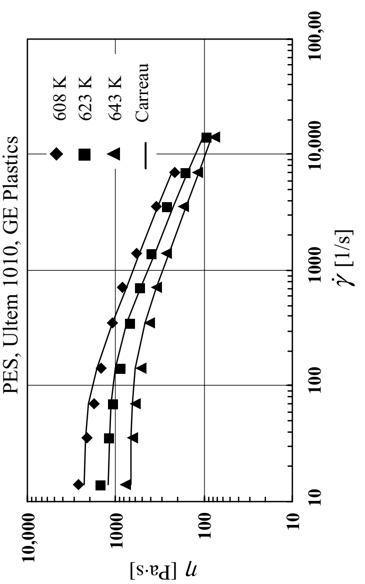


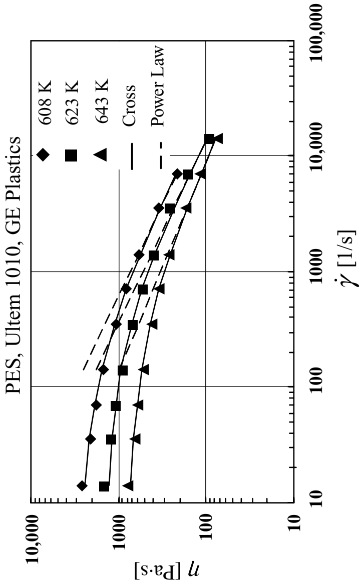
TPE, Riteflex, Ticona

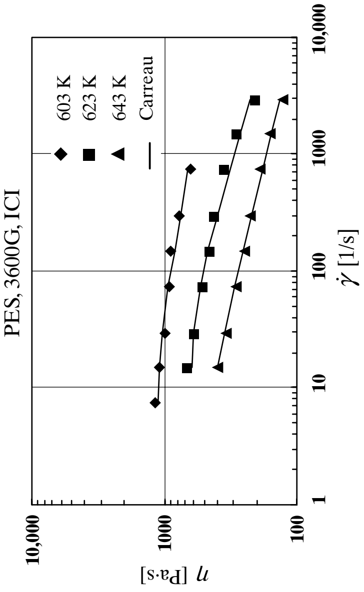


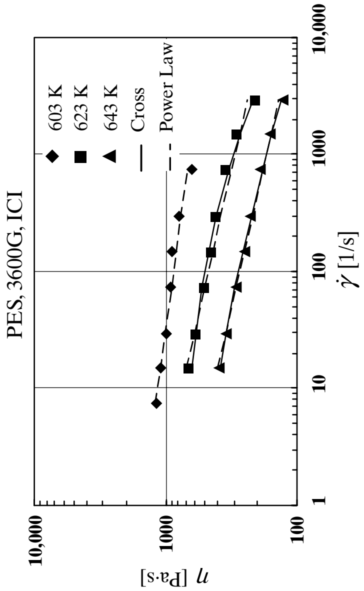
TPE, Riteflex, Ticona

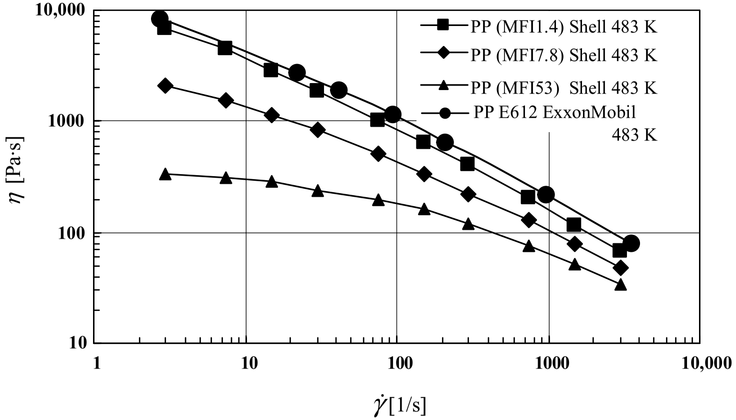


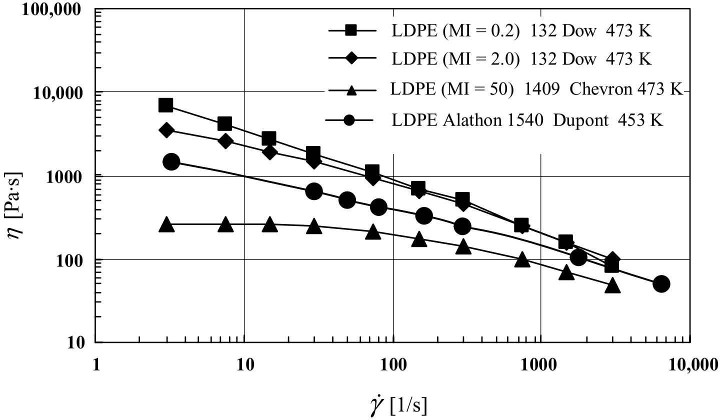

PES, Ultem 1010, GE Plastics


PES, Ultem 1010, GE Plastics


PES, 3600G, ICI


PES, 3600G, ICI


PP (MFI1.4) Shell 483 K
PP (MFI7.8) Shell 483 K
PP (MFI53) Shell 483 K
PP E612 ExxonMobil 483 K
10,000
1000
100
10
1
10
100
1000
10,000
η [Pa·s]
$\dot{\gamma}$[1/s]


LDPE (MI = 0.2) 132 Dow 473 K
LDPE (MI = 2.0) 132 Dow 473 K
LDPE (MI = 50) 1409 Chevron 473 K
LDPE Alathon 1540 Dupont 453 K
100,000
10,000
1000
100
10
1
10
100
1000
10,000
η [Pa·s]
$\dot{\gamma}$ [1/s]

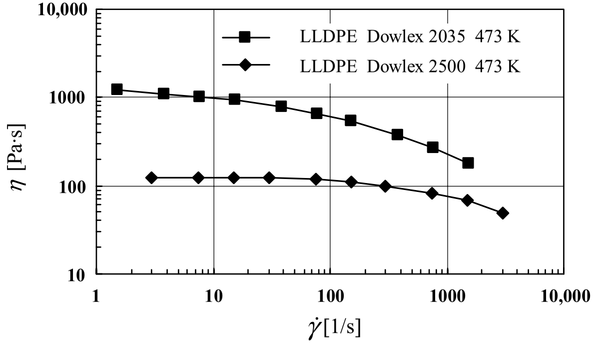

LLDPE Dowlex 2035 473 K
LLDPE Dowlex 2500 473 K
10,000
1000
100
10
1
10
100
1000
10,000
η [Pa·s]
$\dot{\gamma}$[1/s]

TABLE A.2 Thermophysical Properties of Semi-crystalline Thermoplastic Polymers

	Specific Heat [cal/g/°C]		Heat of Fusion	Glass Transition	Melting Point	Crystallization Temp.	Solid Density at 25°C	Melt Density Temp	Melt Density [g/cm^3]		Thermal Conductivity [W/m/ K]		Thermal Diffusivity 10^{-4}[cm^2/s]	
	Solid at 25°C	Melt (average)	[J/g]	[°C]	[°C]	[°C]	[g/cm^3]	[°C]	at 0 psi	at 10^4 psi	Solid	Melt	Solid	Melt
LCP (Xydar)	0.221	0.405	0.39		421–432	357–330	1.68	340	1.590	1.680	0.167	0.233	10.8	8.7
LCP (Vectra)	0.252	0.446	0.48	110	276–286	236	1.408	288	1.320	1.378	0.190	0.260	12.8	10.6
Nylon 6	0.649	0.919	11.6	70	220	182	1.130	240	0.958	1.010	0.317	0.341	10.3	9.3
Nylon 66	0.339	0.638	10.6	48	265	231	1.192	280	1.023	1.090	0.215	0.268	12.7	9.8
PBT	0.286	0.489	10	50	224–236	175	1.292	260	1.147	1.218	0.196	0.240	12.7	10.2
PB-1	0.398	0.628	7.5		118–128	79–58	0.915	160	0.813	0.877				
HDPE	0.453	0.631	39	−120	135	115	0.941–0.968	200	0.767	0.816	0.373	0.324	20.7	16.0
LDPE	0.540	0.600	18.7–23.7	−25	112–114	90–88	0.91–0.92	200	0.763	0.830	0.272	0.220	13.1	11.5
LLDPE	0.450	0.479	23.7		135	86	0.922–0.94	150	0.792	0.866	0.368	0.243	20.8	15.3
PEEK	0.241	0.503	8.5	150	350	310	1.453	370	1.228	1.389	0.251	0.197	17.1	7.6
PET	0.284	0.492	13.7	70	243–248	159	1.308	270	1.211	1.298	0.146	0.289	9.4	11.6
PMP	0.432	0.731	11.8	29	240	164	0.835	285	0.710	0.823	0.285	0.310	18.8	14.2
POM copolymer	0.337	0.526	32.6	−80	168	142	1.385	180	1.195	1.277	0.308	0.291	15.7	11.0
PP	0.421	0.669	21.6	−10	167	101	0.910	210	0.764	0.833	0.298	0.234	18.6	10.9
PPS (40% Filled	0.227	0.420	10.8	91	285	232	1.653	300	1.550	1.627	0.215	0.289	13.7	10.6

TABLE A.3 Thermophysical Properties of Amorphous Thermoplastic Polymers

	Specific Heat [cal/g/°C]		Glass Transition [°C]	Solid Density at 25°C [g/cm^3]	Melt Density Temp [°C]	Melt Density [g/cm^3]		Thermal Conductivity [W/m/ K]		Thermal Diffusivity 10^{-4}[cm^2/s]	
	Solid at 25°C	Melt (average)				at 0 psi	at 10^4 psi	Solid	Melt	Solid	Melt
ABS	0.284	0.445	100	1.226	200	1.154	1.216	0.155	0.205	10.6	9.5
Polyamide-imide	0.247	0.505	272	1.36	360	1.260	1.320	0.218	0.243	15.5	9.1
Polyamide, amorphous	0.314	0.538	155	1.19	260	1.052	1.112				
Polyarylsulfone	0.261	0.480	220	1.29	360	1.192	1.277	0.195	0.238	13.9	10.0
Polyaryester	0.260	0.412	185					0.233	0.243		
Polyetherimide	0.261	0.481	218	1.275	280	1.220	1.287	0.162	0.218	11.6	8.9
Polycarbonate	0.258	0.432	145	1.2	230	1.132	1.207	0.175	0.255	13.5	12.5
Polymethyl-methacrylate	0.307	0.508	105	1.183	200	1.130	1.179	0.172	0.202	11.3	8.4
Polystyrene	0.296	0.499	100	1.067	200	0.970	1.040	0.153	0.185	11.6	9.1
Polyurethane	0.659	0.776		1.26	165	1.073	1.130	0.230	0.247	6.6	7.1
Polyvinylchloride	0.317	0.400	65	1.353	165	1.241	1.307	0.169	0.185	9.4	8.9

Note: For engineering estimates of the dependence of polymer melt density on pressure and temperature use:
Compressibility $\sim 10^{-9}$ (N/m^2)$^{-1}$ $\sim 7 \times 10^{-6}$ (psi)$^{-1}$ and Thermal Expansion Coefficient $\sim 5 \times 10^{-4}$ (K)$^{-1}$

APPENDIX B
Conversion Tables to the International System of Units (SI)

The International System of Units (SI) and Conversion Tables[*]

Quantity	Unit	SI Symbol	
Basic units			
Length	meter	m	
Mass	kilogram	kg	
Time	second	s	
Electric current	ampere	A	
Thermodynamic temperature	kelvin	K	
Luminous intensity	candela	cd	
Supplementary units			
Plane angle	radian	rad	
Solid angle	steradian	sr	
Derived units			
Acceleration	meter per second squared	—	m/s^2
Activity (of a radioactive source)	disintegration per second	—	(disintegration/s)
Angular acceleration	radian per second squared	—	rad/s^2
Angular velocity	radian per second	—	rad/s
Area	square meter	—	m^2
Density	kilogram per cubic meter	—	kg/m^3
Electric capacitance	farad	F	$A \cdot s/V$
Electric field strength	volt per meter	—	V/m
Electric inductance	henry	H	$V \cdot s/A$
Electric potential difference	volt	V	W/A
Electric resistance	ohm	Ω	V/A
Electromotive force	volt	V	W/A
Energy	joule	J	$N \cdot m$
Entropy	joule per kelvin	—	J/K
Force	newton	N	$kg \cdot m/s^2$
Frequency	hertz	Hz	—
Magnetomotive force	ampere	A	—
Power	watt	W	J/s

[*] E. A. Mechtly "The International System of Units," NASA SP-7012, Washington, D.C. 1969; also, *AIChE J.*, **17**, 511 (1971).

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Quantity	Unit	SI Symbol	
Pressure	newton per square meter	—	N/m^2
Quantity of electricity	coulomb	C	$A \cdot s$
Quantity of heat	joule	J	$N \cdot m$
Radiant intensity	watt per steradian	—	W/sr
Specific heat	joule per kilogram-kelvin	—	$J/kg \cdot K$
Stress	newton per square meter	—	N/m^2
Thermal conductivity	watt per meter-kelvin	—	$W/m \cdot K$
Velocity	meter per second	—	m/s
Viscosity, dynamic	Newton-second per square meter	—	$N \cdot s/m^2$
Viscosity, kinematic	square meter per second	—	m^2/s
Voltage	volt	V	W/A
Volume	cubic meter	—	m^3
Wavenumber	reciprocal meter	—	(wave)/m
Work	joule	J	$N \cdot m$

SI Prefixes

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{12}	tera	T	10^{-1}	deci	d
10^{9}	giga	G	10^{-2}	centi	c
10^{6}	mega	M	10^{-3}	milli	m
10^{3}	kilo	k	10^{-6}	micro	μ
10^{2}	hecto	h	10^{-9}	nano	n
10^{1}	deka	da	10^{-12}	pico	p

Physical Constants

	Unit	Value	
Avogadro constant	$k\,mole^{-1}$	6.0222	E + 26*
Gas law constant	$J/kmole \cdot K$	8.3143	E + 3
Boltzmann constant	J/K	1.3806	E − 23
Stefan–Boltzmann constant	W/m^2K^4	5.66916	E − 8
Planck constant	$J \cdot s$	6.6262	E − 34
Gravitational acceleration	m/s^2	9.80665	E + 00

*E + 26 denotes 10^{26}.

Conversion Table to SI Units

To Convert from	To	Multiply by
angstrom	meter (m)	1.000 000* E − 10
atmosphere (normal)	newton/meter^2 (N/m^2)	1.013 250* E + 05
barrel (for petroleum, 42 gal)	meter^3 (m^3)	1.589 873 E − 01
Bar	newton/meter^2 (N/m^2)	1.000 000* E + 05
British thermal unit (International Table)	joule (J)	1.055 04 E + 03
Btu/Ibm-°F (heat capacity)	joule/kilogram-kelvin ($J/kg \cdot K$)	4.186 800* E + 03
Btu/second	watt (W)	1.054 350 E + 03

Conversion Table to SI Units—(*Continued*)

To Convert from	To	Multiply by
Btu/ft^2-hr-°F (heat transfer coefficient)	joule/meter^2-second-kelvin (J/m^2 · s · K)	5.678 264 E + 00
Btu/ft^2-hr (heat flux)	joule/meter^2-second (J/m^2 · s)	3.154 591 E + 00
Btu/ft-hr-deg F (thermal conductivity)	joule/meter-second-kelvin (J/m · s · K)	1.730 735 E + 00
Calorie (International Table)	joule (J)	4.186 800* E + 00
cal/g-°C	joule/kilogram · kelvin (J/kg · K)	4.186 800* E + 03
cal/sec-cm-K	joule/meter-second-kelvin (J/m · s · K)	4.186 800* E + 02
centimeter	meter(m)	1.000 000* E − 02
centimeter^2/second	meter^2/second (m^2/s)	1.000 000* E − 04
centimeter of mercury (0°C)	newton/meter^2 (N/m^2)	1.333 22 E + 03
centimeter of water (4°C)	newton/meter^2 (N/m^2)	9.806 38 E + 01
centipoise	newton-second/meter^2(N · s/m^2)	1.000 000* E − 03
centistokes	meter^2/second (m^2/s)	1.000 000* E − 06
degree Celsius	kelvin (K)	$t_K = t_C + 273.15$
degree Fahrenheit	kelvin (K)	$t_K = (t_F + 459.67)/1.8$
degree Rankine	kelvin (K)	$t_K = t_R/1.8$
dyne	newton (N)	1.000 000* E − 05
dynes/centimeter^2	newton/meter^2 (N/m^2)	1.000 000* E − 01
erg	joule (J)	1.000 000* E − 07
fluid ounce (U.S.)	meter^3 (m^3)	2.957 353 E − 05
foot	meter (m)	3.048 000* E − 01
foot (U.S. survey)	meter (m)	3.048 006 E − 01
foot of water (39.2°F)	newton/meter^2 (N/m^2)	2.988 98 E + 03
foot^2	meter^2 (m^2)	9.290 304* E − 02
foot/second^2	meter/second^2 (m/s^2)	3.048 000* E − 01
foot^2/hour	meter^2/second (m^2/s)	2.580 640* E − 05
foot-pound-force	joule (J)	1.355 818 E + 00
foot^2/second	meter^2/second (m^2/s)	9.290 304* E − 02
foot^3	meter^3 (m^3)	2.831 685 E − 02
gallon (U.S. liquid)	meter^3 (m^3)	3.785 412 E − 03
gram	kilogram (kg)	1.000 000* E − 03
gram/centimeter^3	kilogram/meter^3 (kg/m^3)	1.000 000* E + 03
horsepower (550 ft · $\mathrm{Ib_f}$/s)	watt (W)	7.456 999 E + 02
horsepower-hour	joule (J)	2.6845 E + 06
hour (mean solar)	second (s)	3.600 000 E + 03
inch	meter (m)	2.540 000* E − 02
inch of mercury (60°F)	newton/meter^2 (N/m^2)	3.376 85 E + 03
inch of water (60°F)	newton/meter^2 (N/m^2)	2.488 4 E + 02
inch^2	meter^2 (m^2)	6.451 600* E − 04
inch^3	meter^3 (m^3)	1.638 706* E − 05
kilocalorie	joule (J)	4.186 800* E + 03
kilogram-force (kgf)	newton (N)	9.806 650* E + 00
kilowatt-hour	joules (J)	3.600 000 E + 06
liter	meter^3 (m^3)	1.000 000* E − 03
micron	meter (m)	1.000 000* E − 06
mil	meter(m)	2.540 000* E − 05
mile (U.S. statute)	meter (m)	1.609 344* E + 03

Conversion Table to SI Units—(*Continued*)

To Convert from	To	Multiply by
mile/hour	meter/second (m/s)	4.470 400* E − 01
millimeter mercury (0°C) (torr)	newton/meter^2 (N/m^2)	1.333 224 E + 02
minute (angle)	radian (rad)	2.908 882 E − 04
minute (mean solar)	second (s)	6.000 000* E + 01
ohm (international of 1948)	ohm (Ω)	1.000 495 E + 00
ounce-mass (avoirdupois)	kilogram (kg)	2.834 952 E − 02
ounce (U.S. fluid)	meter^3 (m^3)	2.957 353 E − 05
pint (U.S. liquid)	meter^3 (m^3)	4.731 765 E − 04
poise (absolute viscosity)	newton-second/meter^2 (N · s/m^2)	1.000 000* E − 01
poundal	newton (N)	1.382 550 E − 01
pound-force (Ibf avoirdupois)	newton (N)	4.448 222 E + 00
pound-force-second/foot^2	newton-second/meter^2 (N · s/m^2)	4.788 025 E − 01
pound-force-second/inch^2	newton-second/meter^2 (N · s/m^2)	6.894 757 E + 03
pound-mass (lbm avoirdupois)	kilogram (kg)	4.535 924 E − 01
pound-mass/foot^3	kilogram/meter^3 (kg/m^3)	1.601 846 E + 01
pound-mass/foot-second	newton-second/meter^2 (N · s/m^2)	1.488 164 E + 00
pound-mass/foot^2-second (mass transfer coefficient)	kilogram/meter^2-second (kg/m^2 · s)	4.88243 E + 00
psi (pounds per inch^2)	newton/meter^2 (N/m^2)	6.894 757 E + 03
quart (U.S. liquid)	meter^3 (m^3)	9.463 529 E − 04
second (angle)	radian (rad)	4.848 137 E − 06
slug	kilogram (kg)	1.459 390 E − 01
stoke (kinematic viscosity)	meter^2/second (m^2/s)	1.000 000* E − 04
ton (long, 2240 lbm)	kilogram (kg)	1.016 047 E + 03
ton (short, 2000 lbm)	kilogram (kg)	9.071 847 E + 02
torr (mm Hg, 0°C)	newton/meter^2 (N/m^2)	1.333 22 E + 02
volt (international of 1948)	volt (absolute) (V)	1.000 330 E + 00
watt (international of 1948)	watt (W)	1.000 165 E + 00
watt-hour	joule (J)	3.600 000* E + 03
watt/centimeter^2-°K	joule/meter^2-second-K (J/m^2 · s · K)	1.000 000* E + 04

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*An asterisk after the sixth decimal place indicates the conversion factor is exact and all subsequent digits are zero.

APPENDIX C
Notation

Only symbols used repeatedly in the text are included here. Reference is made to the equation, section, or example where the symbol is first used.

a	Temperature dependence coefficient of viscosity parameter m of a Power Law model fluid (3.3-25)
a_T	Time-temperature superposition shift factor (3.3-30)
A	Interfacial area element (E7.1-14)
A	$= dH/dz$ taper of a screw channel in the down channel direction (9.3-31)
A_f	Free area between screws and barrel in an intermeshing twin screw extruder(6.8-6)
A^*	Dimensionless surface area of a deformed bubble (8.10-2)
b	$= a(T_1 - T_0)$ (5.7-25)
b'	$= b/n$ (5.7-43)
Br	Brinkman number Newtonian (E2.7-3); Power Law model (5.7-28)
c_i	Molar concentration of species i. (2.10-1)
c_e	Equilibrium molar concentration (9.4-8)
C_v	Specific heat at constant volume (2.9-16)
C_p	Specific heat at constant pressure (2.9-16)
C_s, C_m	Specific heat of solid and molten polymer (Section 5.1)
C_L	Centerline distance between intermeshing screws (6.8-1)
Ca	Capillary number (Section 7.1; 8.7-2)
d	Diameter
D	Diameter
D	Deformation of a droplet (7.1-14)
D_b	Inside diameter of an extruder barrel (6.3-4)
D_s	$= D_b - 2H$ diameter of the root of the screw
D_f	$= D_b - 2\delta_f$ diameter of the screw at the tip of the flight
De	Deborah number (3.1-23)
D_N	Dispersion index of molecular weight distribution (7.3-9)
Da	Damkohler number (11.2-26)
$\mathscr{D}$	Diffusion coefficient of solvent in molten polymer (8.5-2)
$\mathscr{D}_{AB}$	Binary mass diffusion coefficient in Fick's law (Example 2.4)

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e	Total specific energy of a system (2.9-9)
e	Flight width (6.3-2)
e_v	Rate of viscous heating per unit volume (12.1-7)
E	Total energy of a system (2.9-1)
E	Activation energy
$\hat{E}$	Dimensionless activation energy (11.2-11)
E_n	Separation efficency of n stages (9.4-9)
E_v	Rate of conversion of mechanical energy into heat (E9.1-2)
$\hat{E}_v$	Rate of conversion of mechanical energy into heat per unit mass flow rate (E9.1-7)
$\mathrm{erf}(z)$	error function (E5.2-8)

f	Kinematic coefficient of friction (4.1-7)
f'	Static coefficient of friction (4.1-1)
f_L	Leakage flow correction factor for the pressure flow rate in screw extruders (6.3-28)
$f(t)dt$	External residence time distribution function (Section 7.3)
f_k	Exit passage distribution function (Section 7.3)
$f(\gamma)d\gamma$	Exit strain distribution function (Section 7.3)
$f(\gamma)d\gamma$	external strain distribution function (Section 7.3)
$\boldsymbol{F}$	Force
$F(t)$	Cumulative exit residence time distribution function (7.3-12)
$F(\gamma)$	Cumulative exit strain distribution function (7.3-21)
F_c	Cohesive force of the agglomerate (7.1-21)
F_d	Drag flow shape factor in a screw extruder (6.3-20)
F_d^*	Drag-flow shape factor for co-rotating disk processor (Example 6.12)
F_D	Air drag-force on fiber in fiber-spinning (E14.1-2)
F_h	Hydrodynamic forces acting on a particle in a sheared liquid (7.1-22)
F_k	Cumulative exit passage distribution function (Section 7.3; 7.3-29)
F_N	Normal force (E3.2-12)
F_p	Pressure-flow shape factor in a screw extruder (6.3-21)
F_p^*	Pressure-flow shape factor for co-rotating disk processor (Example 6.12)
F_{DTW}	Volumetric drag-flow correction factor for nonintermeshing twin-screw extruder (6.8-45)
F_{PTW}	Volumetric pressure-flow correction factor for nonintermeshing twin-screw extruder (6.8-46)
$\mathrm{F_0}$	Fourier number (13.1-16)

$\mathbf{g}$	Gravitational acceleration (2.5-7)
g_N	Skewness measure of a molecular weight distribution (7.3-10)
$g(t)dt$	Internal residence time distribution function (Section 7.3)
$g(\gamma)d\gamma$	Internal strain distribution function (Section 7.3)
$g_k(t)$	Passage distribution function in batch systems (Section 7.3)
$g(Z)$	Generating function (7.3-27)
G	Mass flow rate (9.2-1)
G	Dimensionless pressure gradient (E3.6-4)
$G(t)$	Cumulative internal residence time distribution function (7.3-11)
$G(\gamma)$	Cumulative internal strain distribution function (7.3-19)

$G_k(t)$	Cumulative passage distribution function (7.3-23)
$G'(\omega)$	In-phase dynamic modulus (3.1-22)
$G''(\omega)$	Out-of-phase dynamic modulus (3.1-22)
Gz	Graetz number (12.1-17)
h	Heat transfer coefficient (5.2-1)
h	Enthalpy (Section 2.9)
$\hat{h}$	Enthalpy per unit mass (E9.1-4)
h	Half-separation between two rolls (Section 6.4)
H	separation between parallel plates (Example 2.5); channel depth of a screw
H_0	Half-minimum gap between rolls (Section 6.4 and Fig.6.22)
H_1	Half thickness of sheet leaving the roll; also half separation between rolls at point of detachment at axial location X_1 (Section 6.4 and Fig.6.22)
H_2	Half-separation between the rolls at axial location X_2 (Section 6.4 and Fig.6.22)
i_k	Internal-passage distribution function (Section 7.3; 7.3-29)
I	Intensity of segregation (7.4-10)
$I_{en}(\beta)$	Shanon's relative entropy (7.4-18)
I_k	Cumulative internal passage distribution function (Section 7.3)
I_τ	First scalar invariant of the stress tensor (2.6-2)
II_τ	Second scalar invariant of the stress tensor (2.6-3)
III_τ	Third scalar invariant of the stress tensor (2.6-4)
J	Rate of homogeneous nucleation (8.6-1)
J_{Ai}	Mass flux of component A in the i direction relative to the mass average velocity (Example 2.4)
J_n	n^{th}-order Bessel function (Example 2.9)
J_R	Steady state shear compliance (12.2-3a)
k	Boltzmann constant
k	Thermal conductivity in Fourier's law (Example 2.4)
$\bar{k}$	Mean number of passages (7.3-24)
k_c	Mean packing coordination number (7.1-18)
k_s, k_m	Thermal conductivity of solid and molten polymer
K	Ratio of compressive stress in the horizontal direction to compressive stress in the vertical direction in bins and hoppers (4.3-2)
l	Axial direction in single screw extruders (9.2-25)
L	Characteristic length of flow channels
L_s	Lead of a screw (6.3-1)
L^*	Effective capillary length to account for end effect (Section 12.1)
m	Power Law model parameter (3.1-9)
m_0	$m(T_0)$ (3.3-24)
M	Mass
M_x	Concentration of molecules of x-mers (Section 7.3)
$\overline{M}_n$	Number average molecular weight

$\overline{M}_w$	Mean weight average molecular weight
$\overline{M}_z$	Mean z-average molecular weight

$\mathbf{n}$	Unit outward normal vector
n	Power Law model parameter (3.1-9)
n_f	Number of fully filled chambers in counterrotating intermeshing twin screw extruders (10.2-1)
N	Screw speed (frequency of screw rotation) (6.3-4)
N_C	Number of compressions during transit time in co-rotating twin screw extruders (10.3-5)
N_R	Number of screw rotations during transit time in co-rotating twin screw extruders (10.3-4)
Nu	Nusselt number (11.2-19)

p_w	Power input per unit area in parallel plate flow (E2.5-21)
p_w	Power generated by interparticle friction (5.9-1)
P	Pressure (2.5-8)
P_a	Atmospheric pressure
P_w	Total power input; in parallel plate flow (E2.5-22)
$\hat{P}_w$	Power per unit mass flow rate (E9.1-4)
P_1	Vapor pressure of the solute over an ideal solution (8.4-1)
P_1^0	Vapor pressure of the pure solute (8.4-1)

$\mathbf{q}$	Heat flux (2.9-5)
q	Volumetric flow rate in parallel plate flow per unit width (E2.5-9)
q_d	Volumetric drag flow rate in parallel plate flow per unit width (E2.5-10)
q_p	Volumetric pressure flow rate in parallel plate flow per unit width (E2.5-11)
$\hat{q}_h$	Heat added to per unit mass flow rate (E9.1-4)
Q	Volumetric flow rate
Q_d	Volumetric drag flow rate in a screw extruder (6.3-22)
Q_l	Leakage flow rate in a counter rotating intermeshing twin screw extruder (10.2-3)
Q_p	Volumetric pressure-flow rate in a screw extruder (6.3-22)
Q_{ch}	Volumetric flow rate per channel in a co-rotating intermeshing twin screw extruder (6.8-12)
Q_{th}	Theoretical volumetric flow rate in a counterrotating intermeshing twin screw extruder (10.2-2)
Q_D	Volumetric flow rate through an extruder die (9.2-6)

r	Radial coordinate in cylindrical and spherical coordinates
r	Striation thickness (E7.1-21; 7.4-11)
r_e	Critical radius of a bubble (8.7-1)
R	Radius
$R(r)$	Coefficient of correlation (7.4-7)
R_C, R_L	Circumferential and longitudinal radii of curvature (14.2-19)
R_{cr}	Equilibrium critical radius of a bubble (8.9-13)

s	$= 1/n$; n is the Power Law model parameter
S	Surface area

S	Entropy of a system (7.4-12)
$\mathbf{S}_{ED}^{IA}$	Doi-Edwards chain orientation tensor (3.4-7)
$\mathbf{S}_{MSF}$	Molecular Stress Function theory orientation tensor (3.4-10)
S_R	Recoverable strain (12.2-2)
S^2	Variance of samples taken from mixture (7.4-6)
$\mathscr{s}$	Scale of segregation (7.4-9)
sign	function with either plus or minus values
t	Time
t_0	Minimum residence time
$t_{1/2}$	Half life time (Section 11.1)
$t_f(\xi)$	Fraction of time a fluid particle spends in the upper part of a screw channel (9.2-24)
t_D	diffusion characteristic time (11.3-2)
t_G	Characteristic time for heat release in batch reactor (11.2-5)
t_R	Characteristic time for heat removal in batch reactors (11-2-6)
t_{transit}	Transit time of a charge through one lobe of a co-rotating intermeshing twin-screw extruder (10.3-1)
$\bar{t}$	Mean residence time
$\mathbf{T}'$	Traction vector (Section 2.6)
T	Temperature
$\hat{T}$	Dimensionless temperature (11.2-3)
T_g	Glass transition temperature
T_m	Melting point
T_s	Temperature of the solid polymer
T_m	Temperature of the molten polymer
$\mathscr{T}$	Torque (E2.9-12)
u	Internal energy (2.9-9)
$\mathbf{u}'$	Chain deformation vector (3.4-7)
u_i	Dimensionless velocity component
U	Tangential velocity of calender rolls (Section 6.4)
U_1	Viscous-dissipation dimensionless term in polymer melting (5.7-53)
U_2	Dimensionless factor for temperature dependence of drag flow (5.7-51)
$\mathbf{v}$	Velocity vector
v_i	Velocity components
v_l	Velocity component in a screw extruder in axial direction (6.3-24)
V	Volume
V_0	Plate velocity in parallel plate flow (Example 2.5)
V_b	Velocity of the extruder barrel relative to screw (6.3-4)
V_f	Free volume between screws and barrel in an intermeshing twin-screw extruder (6.8-7)
$\boldsymbol{V}_j$	Relative velocity vector between barrel surface and solid bed (9.3-1)
V_{pl}	Axial velocity of the solids in the solids conveying zone of a single-screw extruder (9.3-2)
V_{sz}	Down-channel velocity of the solid bed in a screw extruder (9.3-27)
w_a	Rate of melting per unit area (E5.4-14)

w_L	Rate of melting per unit length in drag-removal melting (5.7-38); in single screw extruders (9.3-14)
w_T	Total rate of melting in pressure-induced melting (5.8-1)
W	Width of flow channel; screw channel width (6.3-2)
W_x	Weight fraction of x-mers (7.3-2)
x, y, z	Cartesian coordinates
$\bar{x}_N$	Number-average molecular chain length (7.3-4)
$\bar{x}_W$	Weight-average molecular chain length (7.3-5)
$\bar{x}_z$, $\bar{x}_{z+1}$	z-average molecular chain lengths (7.3-6)
X	Width of the solid bed (Sections 5.7 and 9.3)
Y_x	Mole fraction of x-mers (7.3-1)
z	Helical length of a screw channel (6.3-3)
Z	Ratio of hydrodynamic to cohesive forces (7.1-27)
Z_T	Down-channel length of melting in single screw extruders (9.3-30)

Greek Letters

α	Thermal diffusivity (E5.2-1)
α	Parameter in the Ellis model (3.3-26)
α	Angle defining the width of the flight tip in intermeshing twin screws (6.8-2 and Fig. 6.43)
α	Angle formed by polymer melts in the entrance region or capillary flow (12.2-5)
β	Parameter for the pressure dependence of viscosity (12.1-5)
γ	Total shear strain (E7.1-9)
$\bar{\gamma}$	Mean shear strain (7.3-20 and 7.3-22)
$\dot{\boldsymbol{\gamma}}$	Rate of deformation tensor (2.7-7)
$\dot{\gamma}$	Shear rate (2.7-11); magnitude of $\dot{\gamma}$ (3.3-21)
$\bar{\dot{\gamma}}$	Mean shear rate (Example 9.2)
$\dot{\gamma}_w$	Shear rate at the wall (E3.1-9)
$\dot{\gamma}_w^*$	Corrected shear at the wall of a capillary (12.1-3)
$\dot{\gamma}_{xy}$	Components of the shear stress tensor (2.7-2)
Γ	Surface tension (2.11-1)
Γ_w	Newtonian shear rate at the wall in capillary flow (E3.1-11)
δ	Thermal penetration depth (E5.3-8)
δ	Melt film thickness (Section 5.7; in singles screw extruders 9.3-34)
δ	Solubility parameter (8.4-3)
δ_f	Radial flight clearance between flight tip and barrel (6.3-27)
$\boldsymbol{\delta}$	Unit tensor (2.5-9)
$\boldsymbol{\delta}_i$	Unit vectors
ΔH_r	Heat released by chemical reaction in a batch reactor ($-\Delta H_r$) (11.2-1)
ΔE	Flow activation energy (3.3-24)
ΔP	Pressure difference over a finite channel length or flow region

ΔP_D	Pressure drop through a die (9.2-6)
ΔT_a	Adiabatic temperature rise in PED (5.9-3)

ε	Porosity of particulate solids (4.5-2)
ε	Separation efficiency of one stage (9.4-8)
$\dot{\varepsilon}$	Uniaxial elongational strain rate (3.1-1)
$\dot{\varepsilon}_{pl}$	Planar elongational strain rate (3.1-6)
$\boldsymbol{\varepsilon}_{bi}$	Biaxial elongational strain rate (3.1-7)

ζ	$= H/H_1$ dimensionless height between nonparallel plates (Example 2.8)
η	Non-Newtonian shear rate-dependent viscosity (3.1-8)
η_0	Zero shear viscosity; Ellis Model (3.3-26); Cross model (3.3-29); Carreau model (3.3-33)
η_∞	Infinite shear rate viscosity; parameter in the Carreau model (3.3-33)
η', η''	Components of complex viscosity $\eta^* = \eta' - i\eta''$ (3.1-21)
$\bar{\eta}$	Elongational viscosity (3.1-26)
$\bar{\eta}^+$	Elongational stress-growth viscosity (3.1-27)

θ	Angle in cylindrical and spherical coordinates
θ	Helix angle of an extruder screw (6.3-1)
θ	Spherical and cylindrical coordinate
θ_b, θ_s	Helix angle of an extruder screw at the barrel surface $(D = D_b)$ and root of the screw $(D = D_s)$ (6.3-1)
Θ	Dimensionless temperature (E5.3-1)

λ	Relaxation time (3.1-23)
λ	Heat of fusion (5.7-10)
λ^*	Modified heat of fusion (5.7-15)
λ^{**}	Modified heat of fusion (5.7-39)
μ	Viscosity of a Newtonian fluid (2.8-1)
μ_f	Viscosity in the flight clearance of a screw extruder (6.3-28)
μ_r	r^{th} moment of a molecular-weight distribution (7.3-3); moment generating function (7.3-28)

ξ	Dimensionless coordinate

$\boldsymbol{\pi}$	$= P\boldsymbol{\delta} + \boldsymbol{\tau}$ the total stress tensor (2.5-8)
$\boldsymbol{\pi}'$	$= -\boldsymbol{\pi}^\dagger$
π_{ij}	Stress tensor components (2.5-10)

ρ	Density
ρ_{s}, ρ_{m}	Density of solid and molten polymer (Section 5.1)
$\boldsymbol{\rho}_i$	Position vector (E7.1-1)

σ	Normal stress in particulate solids (4.1-1)
σ	Tensile strength of an agglomerate (7.1-17)
σ	Stefan-Boltzmann radiation constant (5.2-2)
σ_y	Yield stress (4.1-2)

σ^2	Variance of binomial distribution (7.4-2)
σ_N^2	Molecular weight distribution variance (7.3-8)

τ	Shear stress; magnitude of the stress tensor (2.6-5)
τ_w	Shear stress at wall (E3.1-4)
τ_y	Yield stress (3.3-34)
τ_{ij}	Dynamic stress tensor components (2.5-10)
τ^*	Parameter in the Cross model (3.3-29)
τ_w^*	Corrected shear stress at the wall of a capillary (12.1-1)
$\boldsymbol{\tau}$	Dynamic or deviatoric stress tensor (2.5-8)

ϕ	Spherical coordinate
ϕ	Solids conveying angle (4.9-1; 9.3-2)
Φ_r	Newtonian rate of viscous heating per unit volume

χ_{12}	Flory-Huggins interaction parameter (8.4-3)

$\mathit{\Psi}$	Half the angle bounding the interpenetrating region between intermeshing screws (6.8-1 and Fig. 6.43)
$\mathit{\Psi}$	Dimensionless number measuring melting rate in singles-screw extruders (9.3-23)
Ψ_1	Primary normal stress coefficient (3.1-10)
Ψ_2	Secondary normal stress coefficient (3.1-11)

$\boldsymbol{\omega}$	Vorticity tensor (2.7-8)
Ω	Angular velocity
Ω	Number of microstates (7.4-12)

Mathematical symbols

D/Dt	Substantial derivative (2.3-2)
$\mathscr{D}/\mathscr{D}t$	Corotational or Jauman derivative (3.3-3)
∇	Vector operator "del" or "nabla" (Footnote 6, Chapter 2)

Abbreviations

ASA	acrylonitrile styrene acrylate
BR	butyl rubber
CAD	computer aided design
CFM	computerized fluid mechanics
CM	continuous mixer
COC	cyclic olefin copolymers
Co-TSE	co-rotating twin screw extruders
CPFR	continuous plug flow reactor
CR-PP	controlled rheology polypropylene
CSTR	continuous stirred tank reactor
CV	control volume
DMF	dimethyl formamide

DMM	dissipative mix-melting
EPDM	ethylene-propylene-diene
EPM	ethylene-propylene monomer
EPOM	engineering polymers oil modified
FAN	flow analysis network
FED	frictional energy dissipation
FEM	finite element method
GMA	glycidyl methacrylate
GRP	glass reinforced polymers
HBR	helical barrel rheometer
HFIP	hexafluoroisopropanol
LCFR	linear continuous flow reactor
LCP	liquid crystal polymers
L/D	length-to-diameter ratio
LDPE	low density polyethylene
LLDPE	linear low density polyethylene
MAH	maleic anhydride
MFR	melt flow rate
MOS	magnesium oxysulfate
MW	molecular weight
MWD	molecular weight distribution
NPD	number of passage distribution
OD/ID	outer-to-inner diameter ratio
PA	polyamide
PBT	polybytylene terephthalate
PC	polycarbonate
PDMS	polydimethylsiloxane
PED	plastic energy dissipation
PEEK	polyetherether ketone
PEI	polyetherimide
PEO	polyethylene oxide
PES	polyethersulfone
PET	polyethylene terephtalate
PETG	glassy PET modified with cyclohexanemethanol
PFR	plug flow reactor
PI	polyimide
PMMA	polymethyl methacrylate
PMP	polymethylpentene
POM	polyoximethylene
POX	peroxide
PP	polypropylene
PPA	polymer processing additive
PPO	polyphenylene oxide
PPS	polyphenylene sulfide
PTFE	polytetrafluorehtylene
PS	polystyrene
PUR	polyurethane
PVC	polyvinyl chloride

RIM	reaction injection molding
RMS	rheometrics mechanical spectrometer
RTD	residence time distribution
SDF	strain distribution function
SIS	styrene-isoprene-styrene block copolymer
SMA	styrene maleic anhydride
SME	screw mixing elements
SSE	single screw extruder
SSMEE	single screw mixing element evaluator
TIM	thermoplastic injection molding
TFR	tubular flow reactor
TGIC	triglycidyl isocyanurate
TSE	twin screw extruder
TSMEE	twin screw mixing element evaluator
VED	viscous energy dissipation

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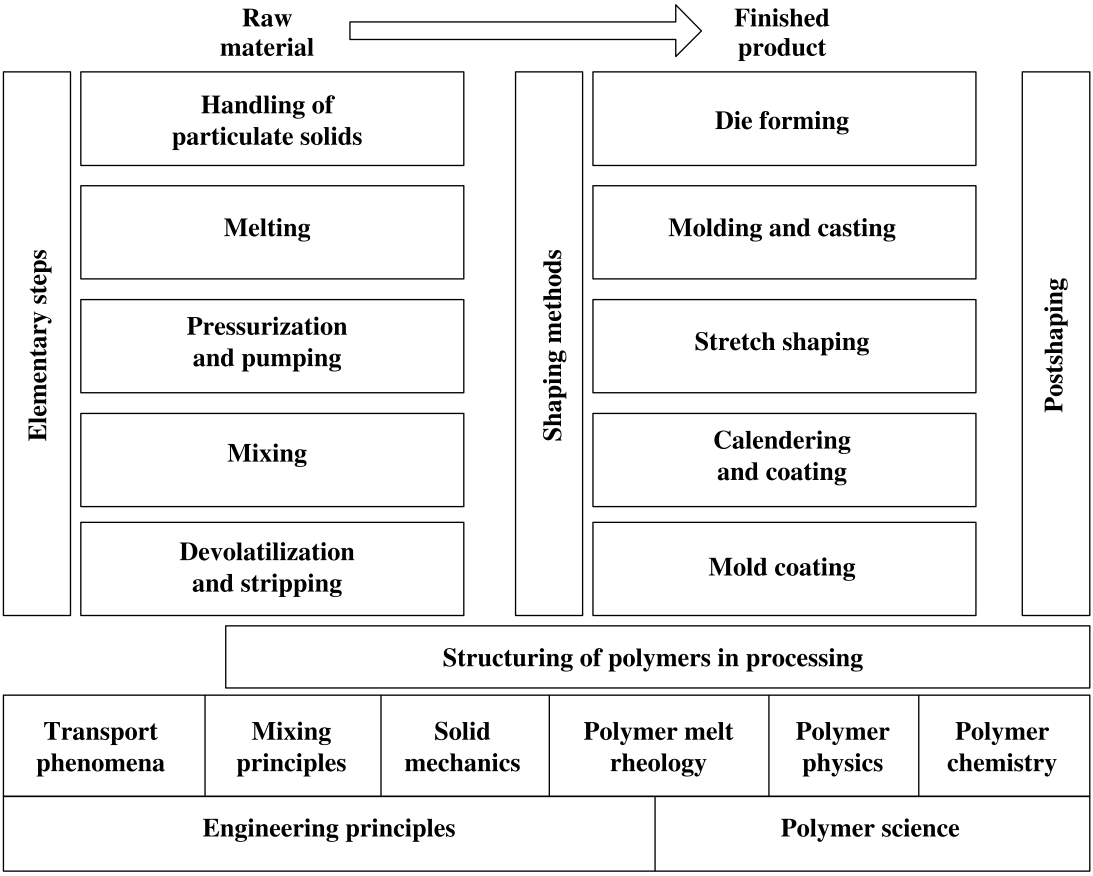
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