

components. A model that accurately fits this behavior is the *Castro-Macosko Curing Model* [8]:

$$\frac{dc}{dt} = k_0 e^{-\frac{E}{RT}} (1-c)^2 \quad (8.11)$$

HEAT TRANSFER DURING CURE

A well-known problem in thermoset components with thick sections is that the exothermic reaction encountered during curing leads to significant temperature rises within the material that may cause thermal degradation. A quick way of estimating the maximum temperature rise that can occur during curing is by using the adiabatic temperature rise given by

$$\Delta T = \frac{Q_r}{C_p} \quad (8.12)$$

where Q_r is the total heat released during reaction and C_p is the specific heat of the resin. Figure 8.17 is a plot of the time to reach 80% cure versus part thickness for various mold temperatures. The shaded area represents the conditions at which the internal temperature within the part exceeds 200 °C as a result of the exothermic reaction. A total heat of reaction of 84,000 J/kg was used in these calculations.

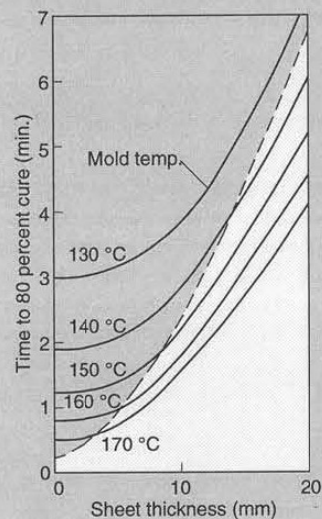


Figure 8.17 Cure times versus plate thickness for various mold temperatures (Shaded region represents the conditions at which thermal degradation can occur [9])

8.4 Compression Molding

Compression molding is widely used in the automotive industry to produce parts that are large, thin, lightweight, strong, and stiff. It is also used in the household goods and electrical industries. Compression molded parts are formed by squeezing a glass fiber reinforced charge inside a mold cavity, as depicted in Fig. 8.18. The matrix can be either a thermoset or thermoplastic. The most common matrix used to manufacture compression molded articles is unsaturated polyester sheet reinforced with glass fibers, known as sheet molding compound (SMC).

The 25 mm long reinforcing fibers are randomly oriented in the plane of the sheet and make up for 20-30% of the molding compound's volume fraction. A schematic diagram of an SMC production line is depicted in Fig. 8.19 [10]. When producing SMC, the chopped glass fibers are sandwiched between two carrier films previously coated with unsaturated polyester-filler matrix. A fiber reinforced thermoplastic charge is often called a glass mat reinforced thermoplastic (GMT) charge. The most common GMT matrix is polypropylene.

During processing of thermoset charges, the SMC blank is cut from a preformed roll and is placed between heated cavity surfaces. Generally, the mold is charged with 1 to 4 layers of SMC, each layer about 3 mm thick, which initially cover about half the mold cavity's surface. During molding, the initially randomly oriented glass fibers orient, leading to anisotropic properties in the finished product. When processing GMT charges, the preforms are cut and heated between radiative heaters. Once heated, they are placed inside a cooled mold that rapidly closes and squeezes the charges before they cool and solidify.

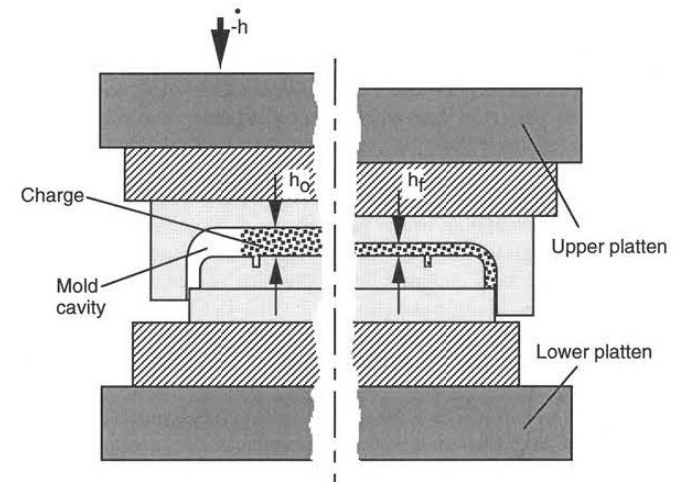


Figure 8.18 Compression molding process (h_0 = charge thickness, h_f = part thickness, and h = closing speed) EG_000216603

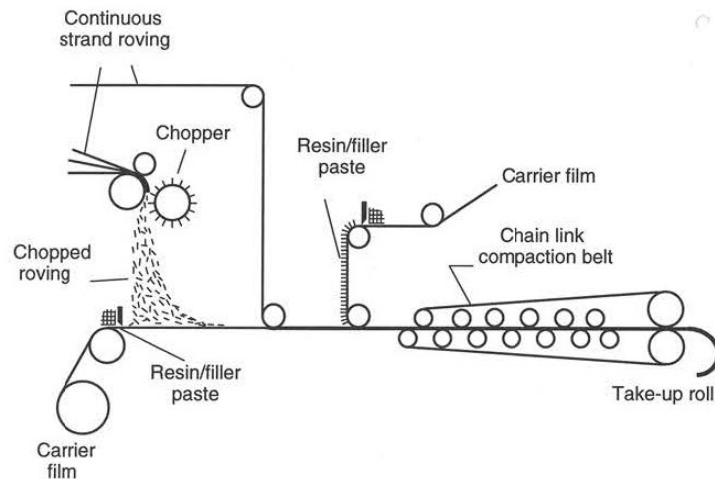


Figure 8.19 SMC production line

One of the main advantages of the compression molding process is the low fiber attrition during processing. Here, relatively long fibers can flow in the melt without the fiber damage common during plastication and cavity filling in injection molding.

An alternate process is injection-compression molding. Here, a charge is injected through a large gate followed by a compression cycle. The material used in the injection compression molding process is called bulk molding compound (BMC), which is reinforced with shorter fibers, generally 1 cm long, with an unsaturated polyester matrix. The main benefit of injection compression molding over compression molding is automation. The combination of injection and compression molding leads to lower degrees of fiber orientation and fiber attrition compared to injection molding.

As in any polymer process, in compression molding there is a direct relationship between deformation and final orientation in the part. Figure 8.20 depicts the fiber orientation distribution within a plate where the initial charge coverage was 33% [11]. Such distribution functions are very common in compression or transfer molding and lead to high degrees of anisotropy throughout a product. To illustrate the effect of fiber orientation on material properties of the final part, Fig. 8.21 [12] shows how the deformation and resulting orientation from 33, 50, 66 and 100% mold coverage affects the stiffness of the plate.

Similar to injection molding, today, there are commercially available codes that can be used to predict mold filling, fiber orientation and warpage of compression molded parts. To predict fiber orientation in realistic parts, the Folgar-Tucker [13] model has been implemented into commercially available compression mold filling simulation programs. The predicted fiber orientation distribution field for a compression molded automotive fender is shown in Fig. 8.22 [14].

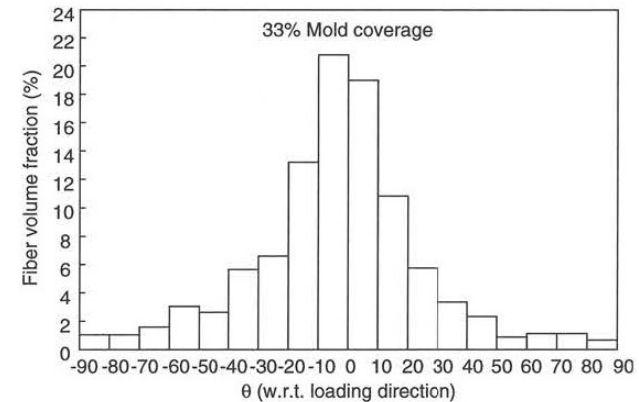


Figure 8.20 Measured fiber orientation distribution histogram in a plate with 33% initial mold coverage and extensional flow during mold filling.

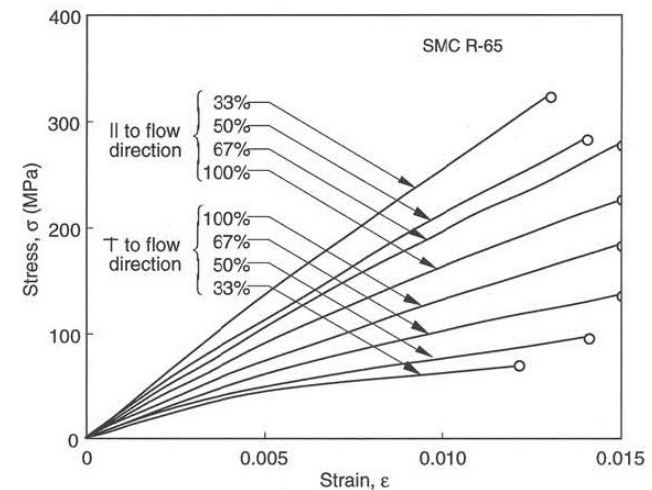


Figure 8.21 Stress-strain curves of 65% glass by volume SMC for various degrees of deformation.

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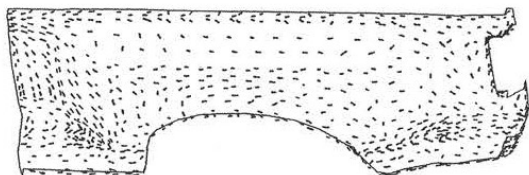


Figure 8.22 Fiber orientation distribution in a compression molded automotive fender.

To calculate the residual stress development during the manufacturing process, and shrinkage and warpage of the finished product commercially available programs use models where the heat transfer equation is coupled to the stress-strain analysis through constitutive equations. Figure 8.23 compares the mold geometry with the part geometry for the truck fender shown in Fig. 8.22, after mold removal and cooling, computed using numerical models[15].

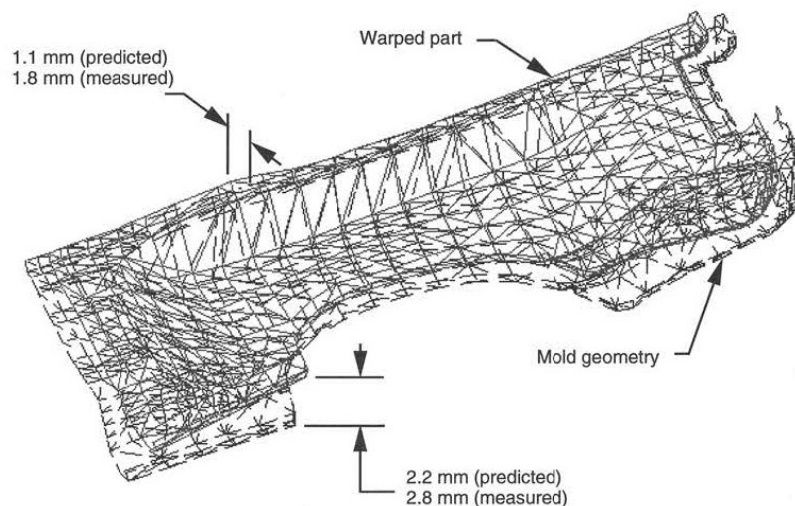


Figure 8.23 Simulated displacements of an automotive body panel. Displacements were magnified by a factor of 20.

8.5 Foaming

In foam or a foamed polymer, a cellular or porous structure has been generated through the addition and reaction of *physical* or *chemical blowing agents*. The basic steps of foaming are cell nucleation, expansion or cell growth, and cell stabilization. Nucleation occurs when, at a given temperature and pressure, the solubility of a gas is reduced, leading to saturation, expelling the excess gas to form a bubble. Nucleating agents, such as powdered metal oxides, are used for initial bubble formation. The bubbles reach an equilibrium shape when their inside pressure balances their surface tension and surrounding pressures. The cells formed can be completely enclosed (closed cell) or can be interconnected (open cell).

A physical foaming process is one where a gas such as nitrogen or carbon dioxide is introduced into the polymer melt. Physical foaming also occurs after heating a melt that contains a low boiling point fluid, causing it to vaporize. For example, the heat-induced volatilization of low-boiling point liquids, such as pentane and heptane, is used to produce polystyrene foams. Also, foaming occurs during volatilization from the exothermic reaction of gases produced during polymerization such as the production of carbon dioxide during the reaction of isocyanate with water. Physical blowing agents are added to the plasticating zone of the extruder or molding machine. The most widely used physical blowing agent is nitrogen. Liquid blowing agents are often added to the polymer in the hopper of the plasticating unit.

Chemical blowing agents are usually powders introduced in the hopper of the molding machine or extruder. Chemical foaming occurs when the blowing agent thermally decomposes, releasing large amounts of gas. The most widely used chemical polyolefin blowing agent is azodicarbonamide.

In mechanical foaming, a gas dissolved in a polymer expands upon reduction of the processing pressure.

The foamed structures commonly generated are either homogeneous foams or integral foams. Figure 8.24 [16] presents the various types of foams and their corresponding characteristic density distributions. In integral foam, the unfoamed skin surrounds the foamed inner core. This type of foam can be achieved during injection molding and extrusion and it replaces the sandwiched structure also shown in Fig. 8.24.

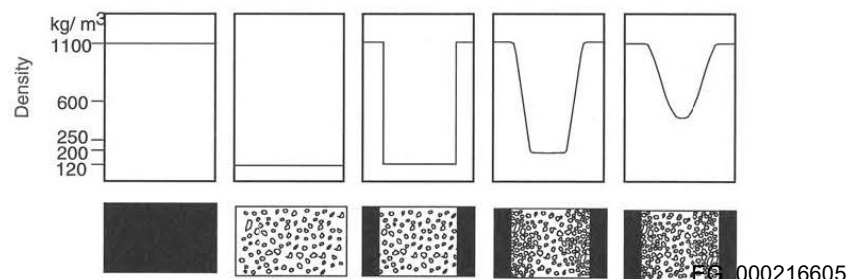


Figure 8.24 Schematic of various foam structures

8.6 Rotational Molding

Rotational molding is used to make hollow objects. In rotational molding, a carefully measured amount of powdered polymer, typically polyethylene, is placed in a mold. The mold is then closed and placed in an oven where the mold turns about two axes as the polymer melts, as depicted in Fig. 8.25. During heating and melting, which occur at oven temperatures between 250 and 450 °C, the polymer is deposited evenly on the mold's surface. To ensure uniform thickness, the axes of rotation should not coincide with the centroid of the molded product. The mold is then cooled and the solid part is removed from the mold cavity. The parts can be as thick as 1 cm, and still be manufactured with relatively low residual stresses. The reduced residual stress and the controlled dimensional stability of the rotational molded product depend in great part on the cooling rate after the mold is removed from the oven. A mold that is cooled too fast yields warped parts. Usually, a mold is first cooled with air to start the cooling slowly, followed by a water spray for faster cooling.

The main advantages of rotational molding over blow molding are the uniform part thickness and the low cost involved in manufacturing the mold. In addition, large parts such as play structures or kayaks can be manufactured more economically than with injection molding or blow molding. The main disadvantage of the process is the long cycle time for heating and cooling of the mold and polymer.

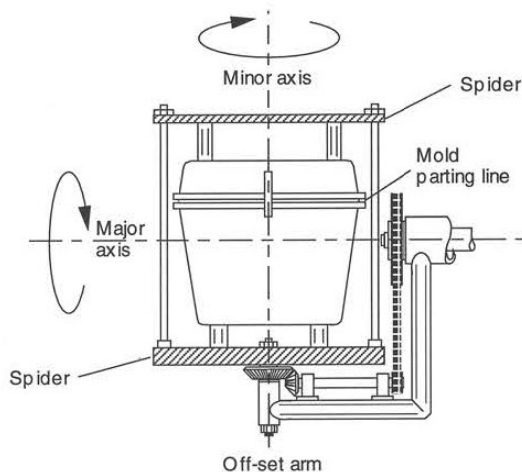


Figure 8.25 Schematic of the rotational molding process

Figure 8.26 presents the air temperature inside the mold in a typical rotational molding cycle for polyethylene powders [17]. The process can be divided into six distinct phases:

- (1) Induction or initial air temperature rise
- (2) Melting and sintering
- (3) Bubble removal and densification
- (4) Pre-cooling
- (5) Crystallization of the polymer melt
- (6) Final cooling

The induction time can be significantly reduced by pre-heating the powder, and the bubble removal and cooling stage can be shortened by pressurizing the material inside the mold. The melting and sintering of the powder during rotational molding depends on the rheology and geometry of the particles. This phenomenon was studied in depth by Bellehumeur and Vlachopoulos [18].

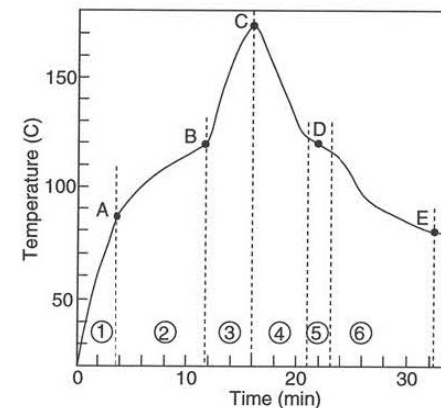


Figure 8.26 Typical air temperature in the mold while rotomolding polyethylene parts

ROTATIONAL MOLDING CYCLE TIME

The cycle time of the rotational molding process is governed by the time it takes to heat and cool the mold and the polymer. Since the mass of the polymer is negligible compared to the mass of the mold, the temperature can be estimated using

$$\left(\frac{T_f - T}{T_f - T_0} \right) = e^{-\frac{hA}{mC_p}t} \quad (8.13)$$

where T is temperature, T_f is the oven temperature (or cooling medium during cooling), T_0 is the initial temperature, h is the convective heat transfer coefficient, A is the outside surface area of the mold, C_p is the specific heat of the mold material, m is the mass of the mold and t is time.

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Examples

- 8.1 A 10 mm thick PVC sheet is fed through a calender formed by 300 mm diameter, 2 meter long rolls, separated by a 5 mm gap. What is the final sheet thickness, and what is the roll separating force if the rolls turn at 60 rpm?

Material data: $m = 17,000 \text{ Pa} \cdot \text{s}^n$ and $n = 0.26$.

Since a sheet of finite thickness is fed to the calender we must use Fig. 8.6 to determine h . If we take an approximate power-law index of 0.25 and $h_f/h_0 = 2$, we read $h/h_0 = 1.085$, which results in a sheet thickness of 5.42 mm.

Next, we compute the roll separating force using Eq. (8.3) along with Fig. 8.4. Figure 8.4 gives $F(0.25) = 5$, so that

$$f = 17,000 \left(\frac{20(1/60)(2\pi)(0.15)}{0.0025} \right)^{0.26} (0.15)(2)(5) = 89.6 \text{ MN}$$

Problems

- 8.1 For the PVC calendering in Example 8.1, determine the roll separation which results in a sheet thickness of 5 mm.
- 8.2 For the PVC calendering in Example 8.1, determine the maximum pressure between the rolls and the power required to drive the system.
- 8.3 A PVC calendering system similar to the one presented in Example 8.1 receives the material in a large roll, leading to a large reservoir. How much power is required to drive the system and what is the roll separating force if a 5 mm thick sheet is required?
- 8.4 What is the metered HDPE film thickness of a reverse roll coating system with 300 mm diameter rolls? Roll 1 rotates at 30 rpm and roll 2 at 90 rpm. The power-law index of HDPE is 0.41 and the surface tension of HDPE in air is 0.0265 N/m.
- 8.5 Will there be any ribbing instabilities in a polypropylene reverse roll coating operation where both rolls rotate at 120 rpm? The power-law index of PP is 0.38, and the surface tension of PP in air is 0.0208 N/m.
- 8.6 Plot the DSC output when measuring the exothermic reaction in an unsaturated polyester for a fixed temperature of 120 °C. Use the following properties:

$$\begin{aligned} a_1 &= 4.9 \times 10^{14} \text{ s}^{-1}, \quad a_2 = 6.2 \times 10^5 \text{ s}^{-1}, \\ b_1 &= 140 \text{ kJ/gmol}, \quad b_2 = 51 \text{ kJ/gmol} \\ m &= 1.3, \quad n = 2.7, \quad Q_r = 84 \text{ kJ/kg}, \quad R = 8.314 \text{ J/gmol/K} \\ \rho &= 1900 \text{ kg/m}^3, \quad C_p = 1000 \text{ J/kg/K}, \quad k = 0.53 \text{ W/m/K} \end{aligned}$$

- 8.7 For the unsaturated polyester data presented in Problem 8.6, plot the exothermic reaction as the temperature is ramped from 20 °C to 150 °C, at a rate of 5 K/min, 10 K/min and 20 K/min.

- 8.8 What maximum possible temperature change can the unsaturated polyester of Problem 8.6 undergo during processing?

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Appendix

Appendices A1 to A5 use the polymer processing concepts covered in this book in a laboratory setting. The five laboratories included here are: extrusion, injection molding, blow molding, thermoforming, and film blowing. These laboratory procedures are written in general terms, and apply to most polymer processing equipment. Each laboratory presents sets of sample data that can be used to compare with your own, or as ersatz data for equipment not available in your facilities.

In most laboratory settings the equipment is much smaller than in industry. Therefore, scale-up must be done when translating learned concepts from the laboratory to an industrial scenario. Table A [1] is an example of scale-up or scale-down factors for polymer extruders where the rate of deformation, and therefore, the viscous dissipation is maintained constant.

Table A. Common Scaling Factors for Extruders [1]

Dimension	Extruder	Scaled Extruder
Diameter	D_1	D_2
Channel width	w_1	$w_2 = w_1(D_2/D_1)$
Channel depth	h_1	$h_2 = h_1(D_2/D_1)^{0.5}$
Screw speed	n_1	$n_2 = n_1(D_1/D_2)^{0.5}$
Output rate	$\dot{m}_1$	$\dot{m}_2 = \dot{m}_1(D_2/D_1)^2$
Shear rate	$\dot{\gamma}_1$	$\dot{\gamma}_2 = \dot{\gamma}_1$
Residence time	t_1	$t_2 = t_1(D_2/D_1)^{0.5}$
Power	P_1	$P_2 = P_1(D_2/D_1)^{2.5}$

Appendix A6 includes transport phenomena equations commonly used when deriving governing equations in polymer processing. For your reference several material property tables are given in Appendix A7.

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A1 Extrusion Laboratory

The primary concern in an extrusion operation is maximizing throughput while maintaining product homogeneity, without generating excessive viscous dissipation. A constant mass throughput must also be maintained to achieve a product of uniform cross section.

A1.1 Objective

The objective of this laboratory is to determine the screw and die characteristic curves, and power requirement, for an HDPE by varying the screw speed and the valve restriction at the end of the extruder.* The temperature distribution at the screw tip and the pressure distribution along the barrel helps visualize the physical processes of extrusion.

A1.2 Laboratory Equipment

A1.2.1 Extruder

This laboratory examines the extrusion process with the Extrudex ED-N-45-25D extruder depicted in Fig.A1.1. This is a 45 mm diameter extruder with an L/D of 25. The screw in the extruder is the plasticating screw described in Table A1.1. Although the general principles in this laboratory apply to all extruders, individual running instructions for your machine must also be followed.

Table A1.1 Screw geometry

Section	Length	Depth (mm)
Feed section	8D	7
Melting section	11D	7-3
Metering section	6D	3

The extruder used in this experiment has an adjustable torpedo die which simulates dies of different restriction. In the notation used below, 0/0 (turns/degrees) implies a closed valve, equivalent to closed discharge. The extruder comes equipped with a series of pressure transducers and thermocouples along the barrel and in the die. They are located at 12D, 16D, 20D, 22D, and 25D. A zero pressure is assumed at 5D. Temperature

* **Caution:** The high temperatures associated with extrusion can injure. Do not manipulate the parameters and components of the extruder unless so instructed. Wear safety glasses when in the laboratory.

profiles across the barrel are measured with 5 thermocouples in the radial direction located 2D after the end of the screw.



Figure A1.1 Extrusion set-up

A1.2.2 Material

The experiments presented here were all performed with an HDPE. The HDPE has a power-law index, n , of 0.41 and a consistency index, m , of 16,600 Pa-s ^{n} at a temperature of 210 °C.

A1.2.3 Utilities

A typical extruder employs electricity, water, and compressed air. The water cools the feed-throat near the hopper and the compressed air often cools the barrel in extruders without blowers. The extruder in this laboratory has blowers.

Before beginning check:

- that barrel zone temperatures have reached the set points indicated on the laboratory procedure handout
- that the hopper is about half full of plastic pellets

A1.3 Experimental Procedure

Initial Settings

The temperature settings in the different heating zones along the barrel must be held constant throughout the experiments. These settings are in Table A1.2.

Table A1.2 Heating zone temperature settings

Zone	Temperature (°C)
Feed section	160 and 170
Melting section	180 and 190
Metering section	200
Thermocomb section	200
Die	200

Step 1

Once the desired temperatures are reached, set the die to 10 turns 0 degrees (10/0). Set the screw speed to 30 rpm and measure the mass throughput by weighting the extrudate that emerges from the die in one minute. Record the following:

- Mass throughput, kg/hr
- Screw torque, N-m
- Temperature of the polymer at the screw tip, °C
- Pressure profile along the barrel, bar

Step 2

Repeat Step 1 for 60, 90, and 120 rpm.

Step 3

Repeat Steps 1 and 2 with die settings of 3/180 and 2/180. Data collected for the experimental set-up and material described above are in Table A1.3.

Step 4

Plot the die and screw characteristic curves

Step 5

Plot the pressure profile along the barrel for all die restrictions at a screw speed of 90 rpm. Repeat for all screw speeds and for a die restriction of 2/180.

Step 6

Plot the temperature distribution at the screw tip for all die restrictions and a screw speed of 90 rpm. Repeat for all screw speeds and for a die restriction of 2/180.

Table A1.3 Data for single screw extruder.

N	X	$\dot{m}$	T	P1	P2	P3	P4	P5	T1	T2	T3	T4	T5
30	10/0	9.75	0.25	72	103	124	94	53	222	195	196	194	211
60	10/0	19.35	0.33	87	133	151	104	78	223	193	193	193	211
90	10/0	29.20	0.39	108	154	158	115	105	219	183	190	192	207
120	10/0	38.80	0.43	126	171	168	122	134	217	180	188	193	207

N	X	$\dot{m}$	T	P1	P2	P3	P4	P5	T1	T2	T3	T4	T5
30	3/180	9.00	0.25	140	176	182	112	71	234	198	198	196	223
60	3/180	17.95	0.33	173	224	217	130	91	232	195	196	195	219
90	3/180	26.75	0.39	200	254	241	151	118	229	190	194	196	216
120	3/180	35.65	0.43	225	280	257	161	151	227	178	195	199	214

N	X	$\dot{m}$	T	P1	P2	P3	P4	P5	T1	T2	T3	T4	T5
30	2/180	8.20	0.25	213	250	241	137	86	238	201	200	198	227
60	2/180	16.40	0.34	260	315	290	157	101	236	200	201	200	225
90	2/180	24.60	0.39	293	355	320	192	133	234	197	200	201	221
120	2/180	32.40	0.43	321	381	331	196	156	231	191	197	203	212

N = screw speed (rpm), X = die opening (0/0 = closed discharge)
 $\dot{m}$ = mass flow rate (kg/hour), T = torque (N-m)
 P_i = pressure along the screw (bars), T_i = temperatures in front of the screw (°C)

A2 Injection Molding Laboratory

A primary concern of the injection molder is to manufacture plastic parts with certain special dimensions. To achieve this one must apply an appropriate sequence of events, which varies with material, during the molding cycle.

A2.1 Objective

This laboratory examines the injection molding of polystyrene (PS). The student will examine the injection molding process, produce several test specimens, and investigate the effect of process variables on part quality and processability.* This laboratory aims to control the part dimensions by varying the pack/hold pressure and by changing the switchover point. The switchover point is when the injection molding machine switches from a constant injection screw speed to a constant injection pressure. These adjustments are depicted in Fig. A2.1, which relates the cycle to the screw position.

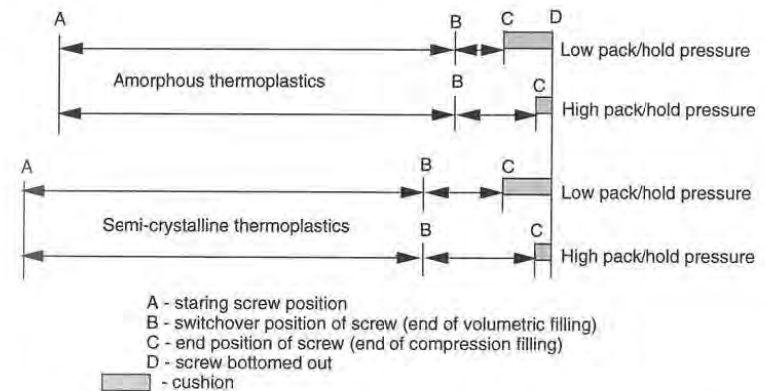


Figure A2.1 Screw movement for amorphous and semi-crystalline thermoplastics

* **Caution:** The high temperatures associated with the injection molding machine can injure. Do not manipulate the parameters and components of the injection molding machine unless so instructed. Wear safety glasses when in the laboratory.

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A2.2 Laboratory Equipment

A2.2.1 Injection Molder

In this example laboratory a Boy 22S injection molding machine, depicted in Fig. A2.2, is used. However, this laboratory applies to most injection molding machines and individual running instructions for the machine in your laboratory must be followed.

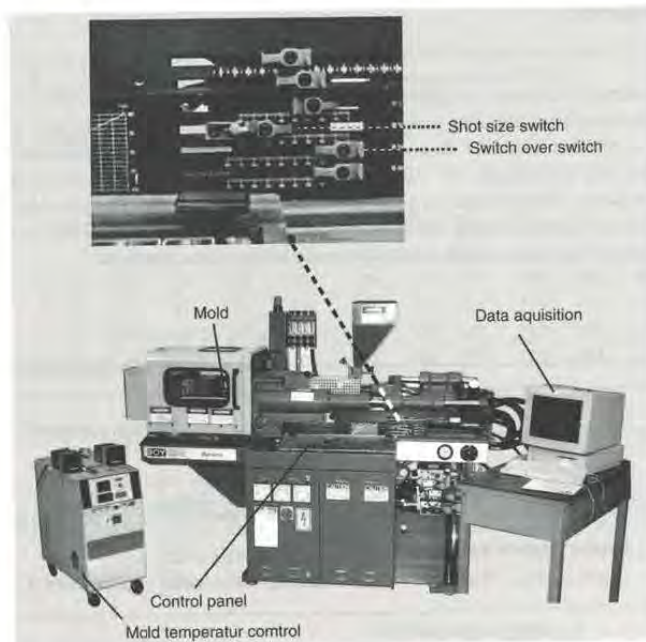


Figure A2.2 Injection molding machine

The mold used for these sample runs was for the flexural bar depicted in Fig. A2.3, and was equipped with two pressure transducers, one near the gate and the second at the end of the mold cavity. The pressure transducers are flush-mounted within the stationary half of the mold cavity that defines the flexural bar. Each pressure transducer must be calibrated before tests start. The pressure transducers are deployed inside the mold cavity to measure polymer pressure during filling, packing, and cooling.

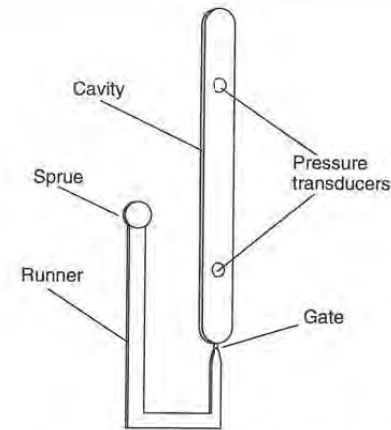


Figure A2.3 Schematic of the mold cavity

A2.2.2 Utilities

A typical injection molder uses electricity and water. The water cools the feed-throat by the hopper. Hydraulic oil is also used for this purpose.

First check that:

- the temperatures of the barrel zones should have reached the set points indicated on the laboratory procedure handout
- the hopper is about half full of plastic pellets
- the mold cavity is empty, which must be checked after every cycle

A2.3 Experimental Procedure

Semi-Automatic Operation:

To initiate operation:

- Press the pump motor start button on the control panel
- Turn the selector dial to the semi-automatic position
- Close the mold safety gate or press the mold close button on the bottom of the control panel. One cycle runs automatically, ending with the specimen ejection

- Ensure that the part has fallen out of the mold cavity. If necessary, carefully pull out the part
- To continue operation, open and close the mold safety gate or press the mold close button

To vary processing times or pressures press the buttons to increase or decrease the values.

To vary shot size or switchover point:

- The shot size switch is usually located below the barrel. An Allen wrench is used to loosen the screw. The shot size is adjusted using a thumb-wheel to slide the switch left or right. The screw must be re-tightened.
- The constant velocity/pressure switchover switch is also located below the barrel. Again, an Allen wrench is used to loosen the screw so the switch can be slid to the left or right. The screw must then be re-tightened.

Initial Settings

The initial base-line settings for all experiments should be:

- Mold temperature = 60 °C
- Melting zone temperature = 150 °C
- Metering zone temperature = 170 °C
- Nozzle temperature = 170 °C
- Shot size = 39 (machine specific units)
- Switchover = 7 (machine specific units)
- Injection speed = 25% of maximum
- Pack/hold pressure = 25% of maximum
- Highest injection pressure allowed = 80% of maximum
- Cooling time = 30 s
- Pack/hold time = 20 s

Step 1

With all the process parameters at their original set-points, observe the pressure trace during the process. Note the shape of the curve at the switchover point and the maximum pressure developed within the cavity. Then observe the cavity pressure traces when the switchover is varied by -2 and +5 from the original switchover value.

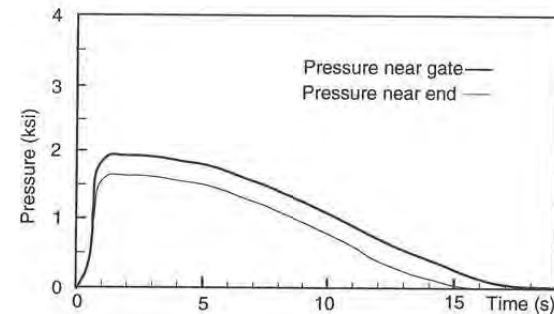


Figure A2.4 Pressure transducer readings with the original settings

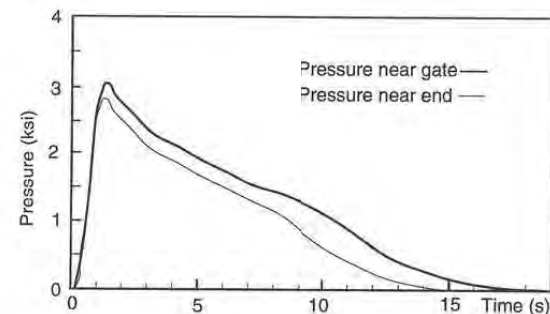


Figure A2.5 Pressure transducer readings with a switchover point at 5 (-2)

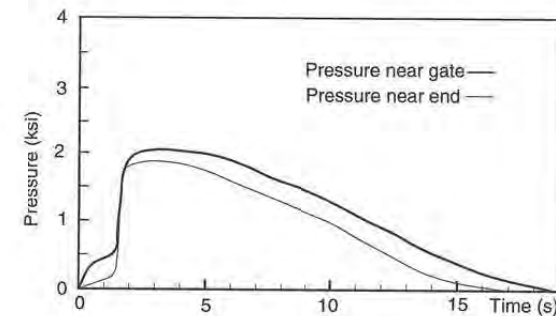


Figure A2.6 Pressure transducer readings with a switchover point at 12 (+7)

Step 2

With all process parameters at their original set-points (including the switchover value), observe what happens to the cavity pressure traces when the shot size is increased by +2 from the original value.

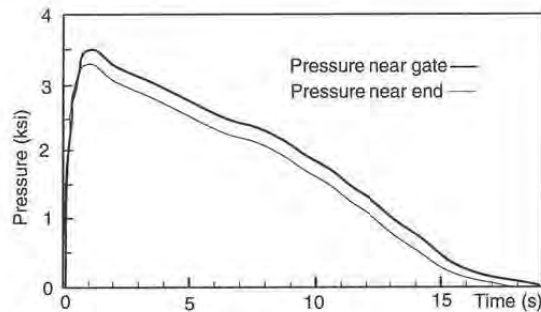


Figure A2.7 Pressure transducer readings with a shot size at 41 (+2)

Step 3

With the pack/hold pressure set at 40% (and the shot size back at its recommended setting), observe the cavity pressure traces as the pack/hold time is decreased in 5 s increments (stop at 5 s). Find acceptable pack/hold time by increasing it in increments of 5 s. Also note if the part becomes difficult to eject.

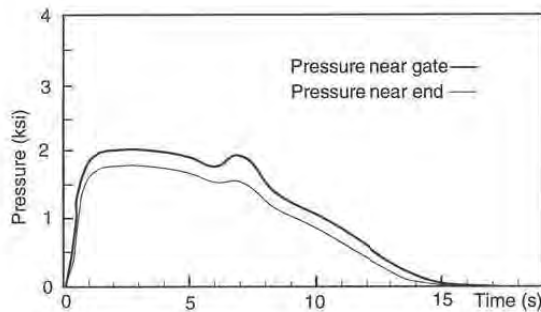


Figure A2.8 Pressure transducer readings with a pack/hold time of 5 s

Step 4

With a pack/hold pressure of 40% and the pack/hold time set as determined in the previous step, observe what happens to the ease of part ejection as the cooling time is

lowered in 5 s increments (stop at 5 s or if part ejection becomes difficult). Set the cooling time to an acceptable value in increments of 5 s.

Step 5

With all settings at their optimized values, determine the influence of pack/hold pressure (at 10, 25, and 40%) on product thickness. Mold three samples at each set of conditions and measure the samples at two different distances from the gate. Sample data is in Table A2.1. Also, weigh the three bars for each set of conditions.

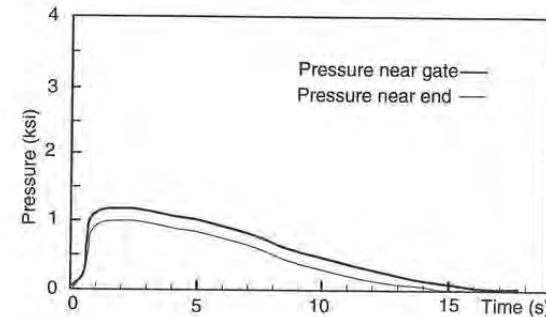


Figure A2.9 Pressure transducer readings with a pack/hold pressure setting at 10%

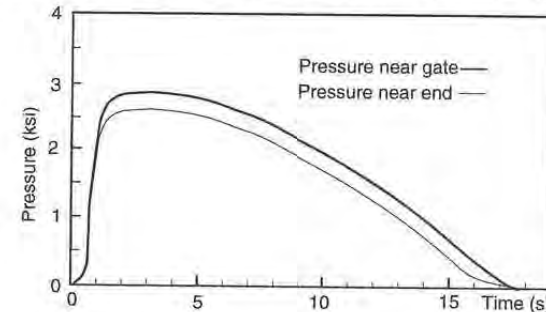


Figure A2.10 Pressure transducer readings with a pack/hold pressure setting at 40%

Step 6

With the time settings determined at the end of step 4 and a pack/hold pressure of 40%, determine ΔP_{fill} . Recall that ΔP_{fill} refers to the pressure loss between transducers 1 and 2 during volumetric filling. Conduct each run three times and record the pressure loss values observed on the data acquisition system. Then lower the mold temperature to

27 °C and run the 40% pack/hold pressure trial again. Allow 15 minutes for the mold temperature to equilibrate. The pressure transducers must now be re-calibrated. Note: Compare part thickness changes at mold temperatures of 60 °C and 27 °C.

Table A2.1 Sample thickness and weight.

Trial	Pressure (%)	Thickness (mm)		Weight (g)
		near gate	mold end	
1	10	3.140	3.114	5.08
2	10	3.140	3.116	5.09
3	10	3.136	3.116	5.08
1	25	3.150	3.136	5.12
2	25	3.144	3.142	5.11
3	25	3.144	3.136	5.11
1	40	3.180	3.168	5.17
2	40	3.176	3.164	5.16
3	40	3.178	3.168	5.17

A3 Blow Molding Laboratory

One of the primary concerns during blow molding is controlling wall thickness distribution within the final article. The ultimate goal can be to obtain a uniform wall thickness with a minimum of material. The wall thickness distribution of a blow molded article influences integrity, performance, and cost.

A3.1 Objective

This experiment demonstrates how several processing variables affect the product quality of a blow molded article, with particular emphasis on how these variables can influence the wall thickness uniformity within the molding.* By measuring the axial and circumferential wall thicknesses for several blow molded articles, the student can gain an understanding of the causes of non-uniform wall thicknesses.

A3.2 Laboratory Equipment

A3.2.1 Blow Molder

In the sample laboratory presented in this section a Rocheleau extrusion blow molding machine, depicted in Fig. A3.1, is used. The procedure described here applies to all extrusion blow molding equipment, however. Auto-timers regulate the time for each stage of the blow molding cycle during the automatic and semi-automatic modes.

A3.2.2 Utilities

The blow molder presented here uses electricity, water, and compressed air. Compressed air inflates the parison and ejects the molded article at the end of the cycle. The air pressure during inflation is controlled via a pressure gauge. Flow rate control valves control the ejector speed. Water is used for cooling.

Setting Screw Rotation Speed and Turn Time:

Before you start the blow molding operation you must set the screw rotation speed and time. At any given screw rotation speed, the screw must rotate enough to extrude the whole parison. The parison must reach just beyond the pinch point at the mold bottom just as the mold closes (Fig. A3.2). The parison must not be so long that material is wasted.

* **Caution:** The high temperatures, high pressures, and moving components associated with the blow molding machine can seriously injure. Do not manipulate the parameters and components of the blow molding machine unless so instructed. Wear safety glasses when in the laboratory.

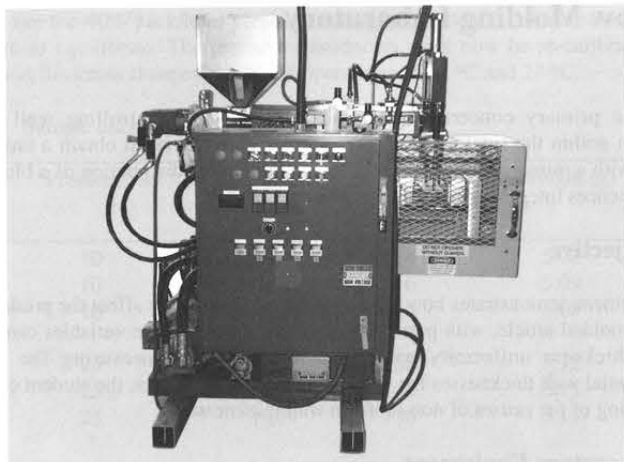


Figure A3.1 Blow molder

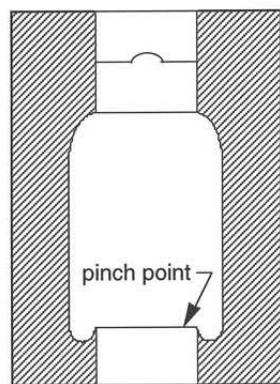


Figure A3.2 Schematic of the bottle mold

A3.3 Experimental Procedure

Manual Operation

Use the manual mode to determine an appropriate screw turn time.

1. Turn the cycle dial to MANUAL and the eject dial to OFF.
2. Press and hold the SCREW TURN button.

3. Release the SCREW TURN button when the parison bottom reaches the mold pinch point.
4. Immediately press and hold the CLAMP button, then press and hold the BLOW button. Hold the BLOW button for the same time indicated on the blow timer.
5. Release the BLOW button but continue to hold the CLAMP button for the time indicated on the air exhaust timer.
6. Release the CLAMP button.
7. Turn the eject dial to DOWN to eject the molded article.

Materials

Two materials are examined. Start the experiment with the polymer that remains in the hopper.

Trial 1. HDPE at the following conditions

Temperature profile (barrel to nozzle): 190, 200, 210 and 210 °C

Blowing pressure: 2.5-2.75 bar (adjust the pressure regulator during the blowing step)

Trial 2. LDPE at the following conditions

Temperature profile (barrel to nozzle): 190, 200, 210 and 210 °C

Blowing pressure: 1.7 bar (adjust the pressure regulator during the blowing step)

Purging the Barrel

After you complete the experiment using one material, you must purge the barrel to introduce the next material.

- Empty the old material from the hopper
- Fill hopper with the new material
- Turn the screw to continuously extrude a parison until the new material appears and the old material has been sufficiently purged.

Step 1

Repeat trials 1 through 2 with screw speeds of 30 and 80 rpm. The parison extrudes as you adjust the screw speed. Remove all of the extrudate from the nozzle once the proper screw speed is set.

Step 2

Check the time needed for extrusion by running the cycle and checking if the parison is properly pinched. However, fine tune the time setting to the nearest 0.5 s once the machine is running in the semi-automatic mode to minimize the trim waste. Starting points for screw turn time are approximately 10 s at a high rpm and 30 s at a low rpm.

Step 3

As soon as the process has been fine tuned, collect two blow molded bottles for each experimental trial. Make sure that you keep track of which side is which on the blow molded products. Record the actual screw rpm and extrusion time used for each experiment. As the parison is extruded through the annular die it will first swell, then sag. The swelling reflects the elasticity of the polymer melt and the sagging reflects the melt viscosity. Hence, polymers are often called viscoelastic. Swelling and sagging influence the product wall thickness, i.e. more swelling and less sagging will thicken the part, and *vice versa*. Note any difficulties encountered while running the trials.

Step 4

Measure the axial wall thickness distribution at five locations along opposite sides of each bottle (90° from the parting line and normal to the bottle surface). The thickness distribution in blow molded articles can be measured with a micrometer or electronically. Also record each bottle weight. Sample measurements are presented in Fig. A3.3.

Step 5

Continue to the next set of processing parameters, changing the material if necessary. Give the system enough time to re-equilibrate when changing the process temperatures. If changing materials, purge the material adequately with the new material. The screw rpm is controlled by a constant torque motor. While purging, note any changes in the screw rpm as the new material is fed into the screw. Once the material is completely purged, return to Step 1.

Step 6

Plot the thickness distribution for all cases. Explain thickness variations within each bottle and between experiments.

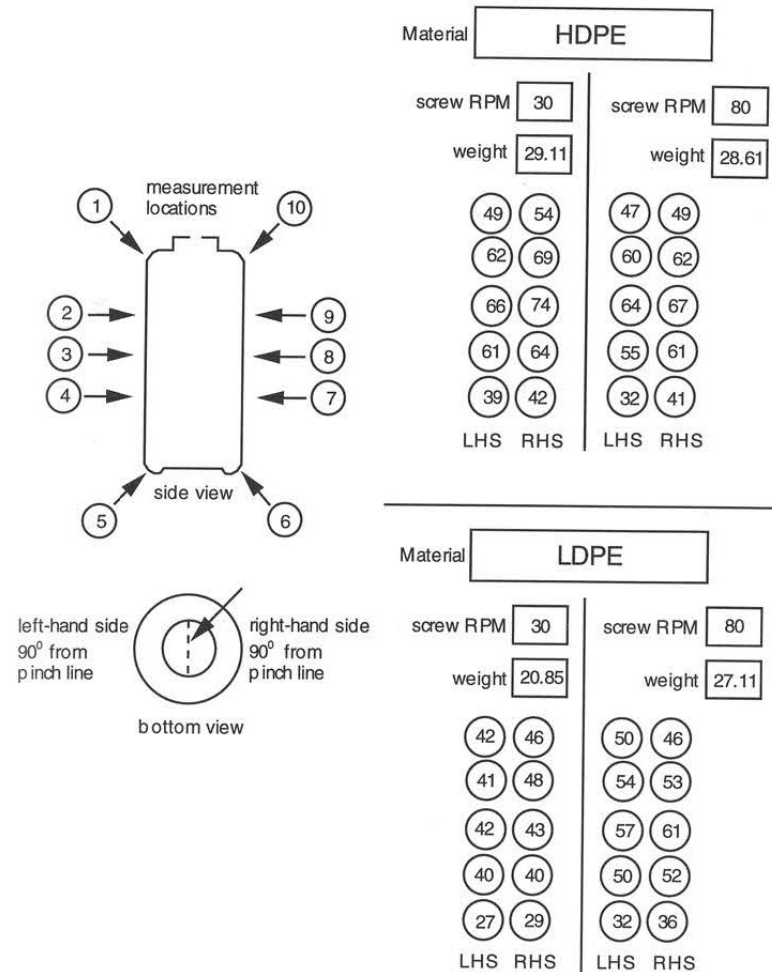


Figure A3.3 Sample measurements

A4 Thermoforming Laboratory

Thermoforming involves drawing a softened sheet of plastic into a mold cavity. To soften the sheet, its temperature is usually raised via radiant heat. Just before shaping, the sheet is positioned over the mold cavity. Wall thickness control and replicating cavity detail are two major concerns when manufacturing a plastic article this way. Vacuum, pressure, or mechanical assists can be used to optimize the shaping.

A4.1 Objective

This thermoforming laboratory aims to produce a thermoformed truncated cone with minimal variation in the thickness distribution. The sequence of events in this thermoforming laboratory starts with the motion of two platens – a lower one onto which a mold cavity is bolted and an upper one onto which a plug is bolted.* The operation can also involve the application of negative or positive pressures to the mold cavity. Furthermore, the speed at which these pressures are applied during the thermoforming process can be varied.

A4.2 Laboratory Equipment

A4.2.1 Thermoforming Machine

In this example laboratory a CAM thermoforming machine, depicted in Figs. A4.1 and A4.2, is used. Although the machine used in the laboratory is much smaller than the ones encountered in industry, it represents the process well. The control console includes the control switches for operation in manual and automatic modes. Before the laboratory, confirm that the set points for all switches agree with those indicated on the laboratory procedure.

Each forming valve (e.g., pre-blow and full vacuum) has a three position selector switch:

- off - valve disabled throughout the entire forming cycle
- on - valve enabled automatically during the forming cycle
- over-ride - valve enabled manually

The automatic action of the forming valves required for a specific thermoforming technique are controlled via platen positions, delay timers, and duration timers. In this experiment, only the full vacuum forming valve is used. This valve rapidly removes air

* **Caution:** The high temperatures and pressures, and moving elements associated with the thermoforming machine seriously injure. Do not manipulate the parameters and components of the thermoforming machine unless so instructed. Be especially cautious of the feed car movement. Wear safety glasses when in the laboratory.

from the cavity which causes the sheet to draw against the cavity walls. The feedback temperature controller readily allows you to change the temperature set points of the oven.

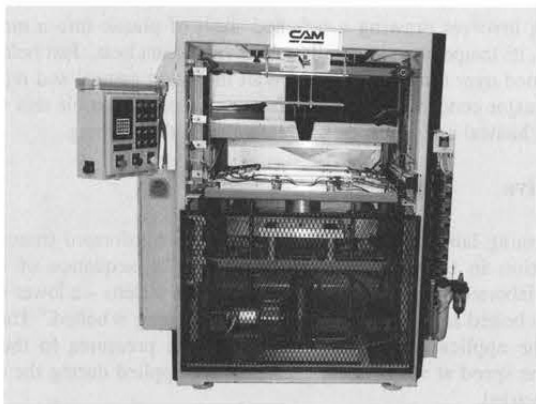


Figure A4.1 Thermoforming machine



Figure A4.2 Close-up of the clamps, mold, and plug assist of the thermoforming machine

A4.2.2 Utilities

Most thermoforming machines use electricity and compressed air. The compressed air is used in many areas of the process, such as the vacuum pump, the sheet clamps in the sled, the sled motion, and the platen motion.

A4.3 Experimental Procedure

Running a Cycle

Manual Operation

- Load a plastic sheet in the feed car
- Turn the switch to MANUAL if the manual indicator light is off
- Move the CLAMPS switch to CLOSE
- Move the FEED CAR switch to OVEN. Leave the sheet in the oven for the right amount of time. This depends on the sheet thickness. For the 2 mm (0.080") thick, high impact polystyrene sheet, the heating time is between 90 and 100 s
- Move the FEED CAR switch back to FORM
- Move the TOP PLATEN switch to CLOSE
- Move the MAIN VACUUM switch to OVER-RIDE for 10 seconds
- Turn the MAIN VACUUM switch off
- Move the TOP PLATEN switch back to OPEN
- Move the CLAMPS switch back to OPEN
- Carefully remove the formed plastic sheet from the feed car

Automatic Operation:

- Confirm the set points for the forming valves on the control console
- Confirm the temperature set points, and wait for the temperature to stabilize if necessary
- Make necessary changes to the menus in the Operator Interface Unit
- Load a plastic sheet in the feed car

- Turn MODE switch to AUTO if the auto indicator light is off
- Simultaneously press the two cycle buttons on each side of the control panel
- When the cycle is complete, carefully remove the formed plastic sheet from the feed car

Material

High Impact Polystyrene (HIPS) sheets 2 mm (0.080") thick.

Trials

Three different thermoforming methods are examined during the thermoforming laboratory :

1. Vacuum thermoforming
2. Full plug-assist vacuum thermoforming
3. Partial plug-assist vacuum thermoforming

Although only a few thermoforming techniques are examined in this lab, there are many other variations used to produce thermoformed articles of uniform wall thickness. Besides vacuum and plug-assist, pre-blowing of sheet, vacuum bleeding of mold cavity, pressure forming of sheet, and forming of sheet onto a core rather than into a cavity are other methods used in thermoforming.

All trials are run with the oven temperature set a 260 °C. To raise the HIPS sheets to their appropriate forming temperatures requires a certain heating time.

Step 1

Run the HIPS trials according to the following menu settings, and ensure that you keep track of which side is the front of the thermoformed products :

- Trial 1: Set cycle time for heating sheet to 90 s
Set delay time for applying full vacuum to 0 s
- Trial 2: Set cycle time for heating sheet to 100 s
Set delay time for applying full vacuum to 3 s

Step 2

The thermoformed parts must be analyzed for their wall thickness distributions with an electronic or manual micrometer. Sample thickness data and location on the cone are shown in Fig. A4.3 and Table A4.1.

Step 3

The optimum settings for thermoforming should yield a cone with a constant wall thickness. Compare constant thickness cone to the measured values for each trial.

Step 4

Now try to thermoform a cone with an optimum wall thickness. Run at least 3 trials changing the delay time to appropriate values, measuring each cone until your wall thickness is the most uniform. For these trials:

- Set the sheet heating time to 95 s
- Set delay time for applying full vacuum between 0 and 3 s

Step 5

Visually inspect the parts for surface finish and dimensional accuracy and compare these for the different trials.

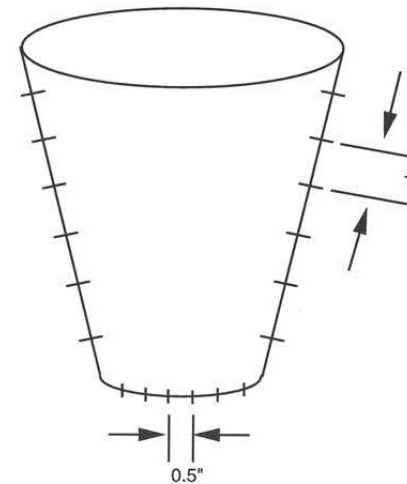


Figure A4.3 Cone locations for thickness measurements

Table A4.1 Thermoforming Laboratory Sample Thickness Data (mills)

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
Heating time:	95	95	95	95	95
Delay time:	0	1	1.5	2	3
Cone:	70	75	57	51	46
(Ovenside)	48	58	47	43	36
	31	41	32	33	31
	15	23	23	28	39
	6	14	21	32	39
	4	9	21	28	20
	3	4	20	21	11
Edge:	2	2	12	10	11
Base:	2	3	15	11	15
	5	3	18	15	17
	3	4	23	20	19
	3	4	21	17	17
	2	3	17	13	13
Edge:	3	3	8	9	10
Cone:	3	4	18	21	12
(Far oven)	4	9	35	34	20
	6	21	28	30	37
	13	23	27	32	30
	30	39	36	27	28
	44	55	42	31	26
	74	74	50	50	47

A5 Film Blowing Laboratory

The primary concern in film blowing is to maximize the mechanical and optical properties and minimize the permeability. The varying process parameters are the draw-down ratio, the bubble pressure, the cooling rates, and hence the blow-up ratio.

A5.1 Objective

This laboratory examines film blowing of low density polyethylene using the film blowing tower shown in Fig. A5.1. The student must vary processing conditions such as take-up speed, bubble pressure and extruder mass throughput, and find the effect of these process variations on film thickness. The results can be presented on dimensionless graphs, such as Figs. 7.7 and 7.8, shown for the Newtonian case in Chapter 7.

A5.2 Laboratory Equipment

In this laboratory, a one inch Killion extruder is used along with a film blowing die and tower. The annular die, that extrudes a 0.5" diameter tube through a 0.015" slit, is attached to a cooling unit such as shown in Fig. A5.2. The film is blown into its final diameter above the die, collapsed by a system of guider rollers and pulled by 2 rollers at a known take-up speed. The material throughput is controlled using the extruder screw speed, the take-up speed by the roller speed and the internal bubble pressure using a valve connected to an air supply. The internal bubble pressure is measured using a water manometer. Under steady-state conditions, the air mass contained between the die and the rollers is constant and the air leakage is compensated by occasionally injecting air into the bubble. Cooling is generally achieved by forced convection from air blown through a ring just above the die.

A5.2.2 Utilities

The extruder uses electricity, water and compressed air. The water is used to cool the feed-throat area by the hopper and the compressed air is used, for extruders without blowers, to cool the barrel. The film blowing die and tower use electricity and compressed air.

First, check:

- that the temperatures of the barrel zones have reached the set points indicated on the laboratory procedure handout
- that the hopper is about half full of plastic pellets

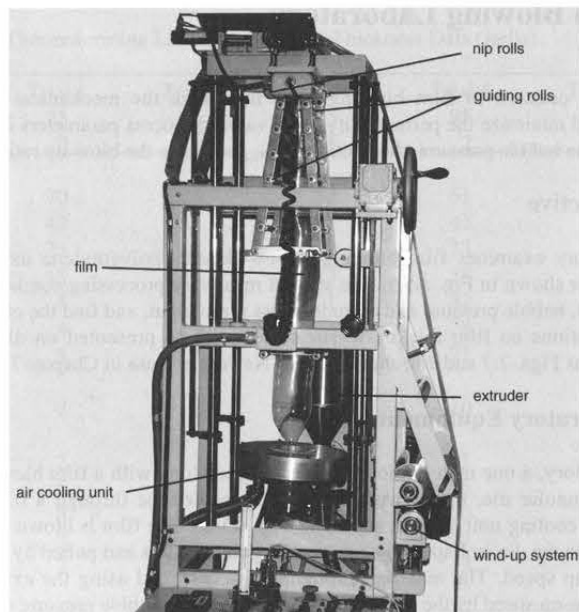


Figure A5.1 Film blowing tower

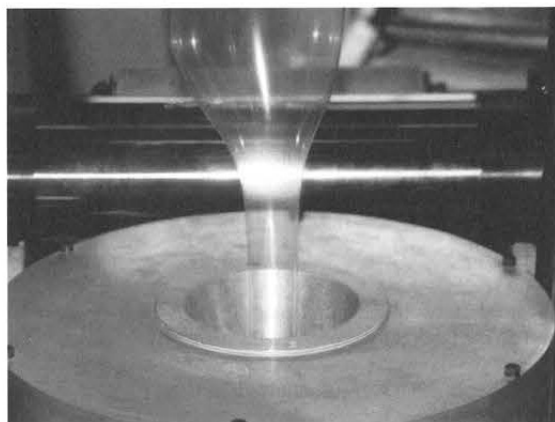


Figure A5.2 Detail of air cooling unit and film

A5.3 Experimental Procedure

Processing Conditions

Initial processing conditions:

Set the barrel heater temperatures to 160°C in feed section, 175°C in the transition zone and 175°C in the metering zone, and the die temperature to 115°C.

Step 1

- Once the heaters reach the desired temperature, set the screw speed to 30 rpm
- Take an old film that runs through the guider, the upper roller system (upper nip) and the lower roller system (lower nip) and stick it to the polymer melt emerging from the die.
- Start the upper roller system and close the rollers after the new extrudate goes through the nip. Use an initial roller speed of 3 feet/min.
- Close the lower nip, ensuring the lower and upper rollers have the same speed

Step 2

Slowly open the air valve until the bubble pressure reaches approximately 6 inches of water. After 20 seconds, when the bubble is fully developed from the die to the upper nip, decrease the bubble pressure to 0.5 inches of water. At the lower pressures, the micro-manometer is turned to the slant position, so the pressures can be read from the finer scale.

Step 3

Start the blower and adjust the speed to maintain a smooth bubble shape.

Step 4

Record the following data (Sample data is presented in Table A5.1):

- Mass flow rate
- Bubble diameter
- Take-up speed
- Bubble pressure
- Position of freezing line (position of stable bubble shape)

Step 5

Plot the blow-up ratio as a function of the thickness reduction as shown in the dimensionless graphs of Chapter 7. Use Fig. A5.3* to determine an average viscosity to non-dimensionalize the pressure with Eq. (7.9).

Step 6

Using the conditions given above, change the take-up speed to 10 and 25 feet/min. Plot the results.

Step 7

Using a take-up speed of 10 feet/min, change the bubble pressure to 0.2 and 1.5 inches of water.

Step 8

Using a take-up speed of 10 feet/min, decrease the screw speed and run internal bubble pressures of 0.2, 0.5 and 1.2 inches of water.

Table A5.1 Sample data

$\dot{m}$ (g/min)	D_f (in)	v_f (feet/min)	Δp (in H_2O)	Z (in)
27.8	15.0	3	0.5	9.0
27.9	13.5	10	0.5	6.5
27.5	13.5	25	0.5	8.5
27.8	13.5	10	0.2	11.5
27.6	15.0	10	1.5	4.5
10.2	13.0	10	0.2	6.5
10.6	15.0	10	0.5	5.5
10.7	15.0	10	1.2	4.0

* Meissner, J., *Rheol. Acta*, 10, 230, (1971).

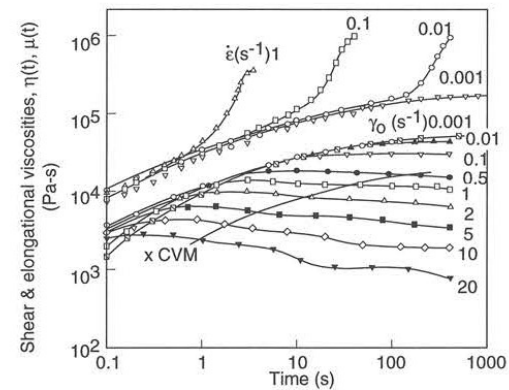


Figure A5.3 Development of elongational and shear viscosities during deformation for polyethylene samples.

A6 Transport Phenomena Equations

ENERGY EQUATION

The Energy Equation

$$\rho C_v \frac{DT}{Dt} = (\nabla \cdot k \nabla T) + \frac{1}{2} \mu (\dot{\underline{\gamma}} : \dot{\underline{\gamma}}) + \dot{Q}$$

The Energy Equation in Terms of Transport Properties

Rectangular coordinates (x,y,z):

$$\rho C_v \left(\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} \right) = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + 2\mu \left(\left(\frac{\partial v_x}{\partial x} \right)^2 + \left(\frac{\partial v_y}{\partial y} \right)^2 + \left(\frac{\partial v_z}{\partial z} \right)^2 \right) + \mu \left(\left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x} \right)^2 + \left(\frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x} \right)^2 + \left(\frac{\partial v_y}{\partial z} + \frac{\partial v_z}{\partial y} \right)^2 \right) + \dot{Q}$$

Cylindrical coordinates (r,θ,z):

$$\rho C_v \left(\frac{\partial T}{\partial t} + v_r \frac{\partial T}{\partial r} + \frac{v_\theta}{r} \frac{\partial T}{\partial \theta} + v_z \frac{\partial T}{\partial z} \right) = k \left(\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} \right) + 2\mu \left(\left(\frac{\partial v_r}{\partial r} \right)^2 + \left(\frac{1}{r} \left(\frac{\partial v_\theta}{\partial \theta} + v_r \right) \right)^2 + \left(\frac{\partial v_z}{\partial z} \right)^2 \right) + \mu \left(\left(\frac{\partial v_\theta}{\partial z} + \frac{1}{r} \frac{\partial v_z}{\partial \theta} \right)^2 + \left(\frac{\partial v_r}{\partial r} + \frac{\partial v_z}{\partial z} \right)^2 + \left(\frac{1}{r} \frac{\partial v_r}{\partial \theta} + r \frac{\partial}{\partial r} \left(\frac{v_\theta}{r} \right) \right)^2 \right) + \dot{Q}$$

CONTINUITY EQUATION

Continuity Equation (Incompressible Fluids)

$$\nabla \cdot \underline{v} = 0$$

Rectangular coordinates

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0$$

Cylindrical coordinates (r,θ,z)

$$\frac{1}{r} \frac{\partial}{\partial r}(rv_r) + \frac{1}{r} \frac{\partial v_\theta}{\partial \theta} + \frac{\partial v_z}{\partial z} = 0$$

EQUATION OF MOTIONEquation of Motion (in terms of $\underline{\tau}$)

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla p + [\nabla \cdot \underline{\tau}] + \rho \mathbf{g}$$

Rectangular coordinates (x,y,z)

$$\rho \left(\frac{\partial v_x}{\partial t} + v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} + v_z \frac{\partial v_x}{\partial z} \right) = -\frac{\partial p}{\partial x} + \left(\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} \right) + \rho g_x$$

$$\rho \left(\frac{\partial v_y}{\partial t} + v_x \frac{\partial v_y}{\partial x} + v_y \frac{\partial v_y}{\partial y} + v_z \frac{\partial v_y}{\partial z} \right) = -\frac{\partial p}{\partial y} + \left(\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} \right) + \rho g_y$$

$$\rho \left(\frac{\partial v_z}{\partial t} + v_x \frac{\partial v_z}{\partial x} + v_y \frac{\partial v_z}{\partial y} + v_z \frac{\partial v_z}{\partial z} \right) = -\frac{\partial p}{\partial z} + \left(\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} \right) + \rho g_z$$

Cylindrical coordinates (r,θ,z)

$$\rho \left(\frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_r}{\partial \theta} - \frac{v_\theta^2}{r} + v_z \frac{\partial v_r}{\partial z} \right) = -\frac{\partial p}{\partial r} + \left(\frac{1}{r} \frac{\partial}{\partial r}(r\tau_{rr}) + \frac{1}{r} \frac{\partial \tau_{r\theta}}{\partial \theta} - \frac{\tau_{\theta\theta}}{r} + \frac{\partial \tau_{rz}}{\partial z} \right) + \rho g_r$$

$$\rho \left(\frac{\partial v_\theta}{\partial t} + v_r \frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_\theta}{\partial \theta} + \frac{v_r v_\theta}{r} + v_z \frac{\partial v_\theta}{\partial z} \right) = -\frac{1}{r} \frac{\partial p}{\partial \theta} + \left(\frac{1}{r^2} \frac{\partial}{\partial r}(r^2 \tau_{r\theta}) + \frac{1}{r} \frac{\partial \tau_{\theta\theta}}{\partial \theta} + \frac{\partial \tau_{\theta z}}{\partial z} \right) + \rho g_\theta$$

$$\rho \left(\frac{\partial v_z}{\partial t} + v_r \frac{\partial v_z}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_z}{\partial \theta} + v_z \frac{\partial v_z}{\partial z} \right) = -\frac{\partial p}{\partial z} + \left(\frac{1}{r} \frac{\partial}{\partial r}(r\tau_{rz}) + \frac{1}{r} \frac{\partial \tau_{\theta z}}{\partial \theta} + \frac{\partial \tau_{zz}}{\partial z} \right) + \rho g_z$$

Equation of Motion (in terms of $\underline{\mathbf{v}}$) (Navier-Stokes Equations)

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla p + \mu \nabla^2 \mathbf{v} + \rho \mathbf{g}$$

Rectangular coordinates (x,y,z)

$$\rho \left(\frac{\partial v_x}{\partial t} + v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} + v_z \frac{\partial v_x}{\partial z} \right) = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2} + \frac{\partial^2 v_x}{\partial z^2} \right) + \rho g_x$$

$$\rho \left(\frac{\partial v_y}{\partial t} + v_x \frac{\partial v_y}{\partial x} + v_y \frac{\partial v_y}{\partial y} + v_z \frac{\partial v_y}{\partial z} \right) = -\frac{\partial p}{\partial y} + \mu \left(\frac{\partial^2 v_y}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} + \frac{\partial^2 v_y}{\partial z^2} \right) + \rho g_y$$

$$\rho \left(\frac{\partial v_z}{\partial t} + v_x \frac{\partial v_z}{\partial x} + v_y \frac{\partial v_z}{\partial y} + v_z \frac{\partial v_z}{\partial z} \right) = -\frac{\partial p}{\partial z} + \mu \left(\frac{\partial^2 v_z}{\partial x^2} + \frac{\partial^2 v_z}{\partial y^2} + \frac{\partial^2 v_z}{\partial z^2} \right) + \rho g_z$$

Cylindrical coordinates (r,θ,z)

$$\rho \left(\frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_r}{\partial \theta} - \frac{v_\theta^2}{r} + v_z \frac{\partial v_r}{\partial z} \right) = -\frac{\partial p}{\partial r} + \mu \left(\frac{1}{r} \frac{\partial}{\partial r} \left(\frac{1}{r} \frac{\partial}{\partial r}(rv_r) \right) + \frac{1}{r^2} \frac{\partial^2 v_r}{\partial \theta^2} - \frac{2}{r^2} \frac{\partial v_\theta}{\partial \theta} + \frac{\partial^2 v_r}{\partial z^2} \right) + \rho g_r$$

$$\rho \left(\frac{\partial v_\theta}{\partial t} + v_r \frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_\theta}{\partial \theta} + \frac{v_r v_\theta}{r} + v_z \frac{\partial v_\theta}{\partial z} \right) = -\frac{1}{r} \frac{\partial p}{\partial \theta} + \mu \left(\frac{1}{r} \frac{\partial}{\partial r} \left(\frac{1}{r} \frac{\partial}{\partial r}(rv_\theta) \right) + \frac{1}{r^2} \frac{\partial^2 v_\theta}{\partial \theta^2} - \frac{2}{r^2} \frac{\partial v_r}{\partial \theta} + \frac{\partial^2 v_\theta}{\partial z^2} \right) + \rho g_\theta$$

$$\rho \left(\frac{\partial v_z}{\partial t} + v_r \frac{\partial v_z}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_z}{\partial \theta} + v_z \frac{\partial v_z}{\partial z} \right) = -\frac{\partial p}{\partial z} + \mu \left(\frac{1}{r} \frac{\partial}{\partial r} \left(\frac{1}{r} \frac{\partial v_z}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 v_z}{\partial \theta^2} + \frac{\partial^2 v_z}{\partial z^2} \right) + \rho g_z$$

A7 Properties Tables

EG_000216626

Table I Guide Values of the Physical Properties of Plastics

Polymer	Abbreviation	Density		Mechanical properties	
		g/cm ³	lb/in ³	Tensile strength	
				N/mm ²	psi
Low density polyethylene	PE-LD	0.914/0.928	0.0329-0.0330	8/23	1140/3270
High density polyethylene	PE-HD	0.94/0.96	0.0338-0.0345	18/35	2560/4980
EVA	EVA	0.92/0.95	0.0331-0.0341	10/20	1420/2840
Polypropylene	PP	0.90/0.907	0.0324-0.0327	21/37	2990/5260
Polybutene-1	PB	0.905/0.920	0.0325-0.0331	30/38	4270/5400
Polyisobutylene	PIB	0.91/0.93	0.0327-0.0334	2/6	284/853
Poly-4-methylpent-1-ene	PMP	0.83	0.0298	25/28	3560/3980
Ionomers	-	0.94	0.0338	21/35	2990/4980
Rigid PVC	PVC-U	1.38/1.55	0.0496-0.0557	50/75	7110/10670
Plasticized PVC	PVC-P	1.16/1.35	0.0417-0.0486	10/25	1420/3560
Polystyrene	PS	1.05	0.0378	45/65	6400/9240
Styrene/acrylonitrile copolymer	SAN	1.08	0.0392	75	10670
Styrene/polybutadiene graft polymer	SB	1.05	0.0378	26/38	3700/5400
Acrylonitrile/polybut./styrene graft polymer	ABS	1.04/1.06	0.0374-0.0381	32/45	4550/6400
AN/AN elastomers/styrene graft polymer	ASA	1.04	0.0374	32	4550
Polymethylmethacrylate	PMMA	1.17/1.20	0.0421-0.0431	50/77	7110/10950
Polyvinylcarbazole	PVK	1.19	0.0428	20/30	2840/4270
Polyacetal	POM	1.41/1.42	0.0507-0.0511	62/70	8820/9960
Polytetrafluoroethylene	PTFE	2.15/2.20	0.0774-0.0791	25/36	3560/5120
Tetrafluoroethylene/hexafluoropropylene copolymer	FEP	2.12/2.17	0.0763-0.0781	22/28	3130/3980
Polytrifluoroethylene	PCTFE	2.10/2.12	0.0755-0.0762	32/40	4550/5690
Ethylene/tetrafluoroethylene	E/TFE	1.7	0.0611	35/54	4980/7680
Polyamide 6	PA 6	1.13	0.0406	70/85	9960/12090
Polyamide 66	PA 66	1.14	0.0410	77/84	10950/11950
Polyamide 11	PA 11	1.04	0.0374	56	7960
Polyamide 12	PA 12	1.02	0.0367	56/65	7960/9240
Polyamide 6-3-T	PA-6-3-T	1.12	0.0403	70/84	9960/11950
Polycarbonate	PC	1.2	0.0432	56/67	7960/9530
Polyethyleneterephthalate	PET	1.37	0.0492	47	6680
Polybutyleneterephthalate	PBT	1.31	0.0471	40	5690
Polyphenyleneether modified	PPE	1.06	0.0381	55/68	7820/9670
Polysulfone	PSU	1.24	0.0446	50/100	7110/14200
Polyphenylenesulfide	PPS	1.34	0.0483	75	10670
Polyarylsulfone	PAS	1.36	0.0490	90	12800
Polyethersulfone	PES	1.37	0.0492	85	12090
Polyarylether	PAE	1.14	0.0411	53	7540
Phenol/formaldehyde, grade 31	PF	1.4	0.0504	25	3560
Urea/formaldehyde, grade 131	UF	1.5	0.0540	30	4270
Melamine/formaldehyde, grade 152	MF	1.5	0.0540	30	4270
Unsaturated polyester resin, grade 802	UP	2.0	0.0720	30	4270
Polydiallylphthalate (GF) molding compound	PDAP	1.51/1.78	0.0543-0.0640	40/75	5690/10670
Silicone resin molding compound	SI	1.8/1.9	0.0648-0.0684	28/46	3980/6540
Polyimide molding	PI	1.43	0.0515	75/100	10570/14200
Epoxy resin, grade 891	EP	1.9	0.0683	30/40	4270/5690
Polyurethane casting resin	PU	1.05	0.0378	70/80	9960/11380
Thermoplastic PU-elastomers	PU	1.20	0.0432	30/40	4270/5690
Linear polyurethane (U ₅₀)	PU	1.21	0.0435	30 (σ ₁)	4270 (σ ₁)
Vulcanized fiber	VF	1.1/1.45	0.0396-0.0522	85/100	12090/14200
Celluloseacetate, grade 432	CA	1.30	0.0468	38 (σ ₁)	5400 (σ ₁)
Cellulosepropionate	CP	1.19/1.23	0.0429-0.0452	14/55	7990/7820
Celluloseacetobutyrate, grade 413	CAB	1.18	0.0425	26 (σ ₁)	3600 (σ ₁)

Elongation at break %	Tensile modulus of elasticity		Ball indentation hardness		Impact strength kJ/m ²	Notched impact strength	
	N/mm ²	kpsi	10-s-value	10-s-value psi		kJ/m ²	ft lb/in of notch
300/1000	200/500	28.4/71.1	13/20	1850/2840	no break	no break	—
100/1000	700/1400	99.6/199	40/65	5690/9240	no break	no break	—
600/900	7/120	0.99/17.1	—	—	no break	no break	—
20/800	11000/1300	156/185	36/70	5120/9960	no break	3/17	no break
250/280	250/350	35.6/49.8	30/38	4270/5400	no break	4/no break	0.5/20
> 1000	—	—	—	—	no break	no break	no break
13/22	1100/1500	156/213	—	—	—	—	no break
250/500	180/210	25.6/29.9	—	—	—	—	0.4/0.6
10/50	1000/3500	142/498	75/155	10670/22000	no break / > 20	2/50	0.4/20
170/400	—	—	—	—	no break	no break	—
3/4	3200/3250	455/462	120/130	17100/18500	5/20	2/2.5	0.25/0.6
5	3600	512	130/140	18500/19900	8/20	2/3	0.35/0.5
25/60	1800/2500	256/356	80/130	11380/18500	10/80	5/13	no break
15/30	1900/2700	270/384	80/120	11380/17100	70/no break	7/20	2.5/12
40	1800	256	75	10670	no break	18	6/8
2/10	2700/3200	384/455	180/200	25600/28400	18	2	0.3/0.5
—	3500	498	200	28400	5	2	—
25/70	2800/3200	398/455	150/170	21300/24200	100	8	1/2.3
350/550	410	58.3	27/35	3840/4980	no break	13/15	3.0
250/330	350	49.8	30/32	4270/4550	—	—	no break
120/175	1050/2100	149/299	65/70	9240/9960	no break	8/10	2.5/2.8
400/500	1100	156	65	9240	—	—	no break
200/300	1400	199	75	10670	no break	no break	3.0
150/300	2000	284	100	14200	no break	15/20	2.1
500	1000	142	75	10670	no break	30/40	1.8
300	1600	228	75	10670	no break	10/20	2/5.5
70/150	2000	284	160	22800	no break	13	—
100/130	2100/2400	299/341	110	15600	no break	20/30	12/18
50/300	3100	441	200	28400	no break	4	0.8/1.0
15	2000	284	180	25600	no break	4	0.8/1.0
50/60	2500	356	—	—	no break	—	4
25/30	2600/2750	370/391	—	—	—	—	1.3
3	3400	484	—	—	—	—	0.3
13	2600	370	—	—	—	—	1/2
30/80	2450	348	—	—	—	—	1.6
25/90	2250	320	—	—	—	—	8.0
0.4/0.8	5600/12000	796/1710	250/320	35600/45500	> 6	> 1.5	0.2/0.6
0.5/1.0	7000/10500	996/1490	260/350	39000/49800	> 6.5	> 2.5	0.5/0.4
0.6/0.9	4900/9100	697/1294	260/410	37000/58300	> 7.0	> 1.5	0.2/0.3
0.6/1.2	14000/20000	1990/2840	240	34100	> 4.5	> 3.0	0.5/16
—	9800/15500	1394/2200	—	—	—	—	0.4/15
—	6000/12000	853/1710	—	—	—	—	0.3/0.8
4/9	23000/28000	3270/3980	—	—	—	—	0.5/1.0
4	21500	3060	—	—	> 8	> 3	2/30
3/6	4000	569	—	—	—	—	0.4
400/450	700	99.6	—	—	no break	no break	no break
35 (ε ₁)	1000	140	—	—	no break	3	—
—	—	—	80/140	11380/19900	20/120	—	—
3 (ε ₁)	2200	313	50	7110	65	15	2.5
30/100	420/1500	59.7/213	47/79	6680/11240	no break	6/20	1.5
4 (ε ₁)	1600	228	35/43	4980/6120	no break	30/35	4/5

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Table I (cont.) Guide Values of the Physical Properties of Plastics

Polymer	Abbreviation	Density	
		g/cm ³	lb/in ³
Low density polyethylene	PE-LD	0.914/0.928	0.0329–0.0330
High density polyethylene	PE-HD	0.94/0.96	0.0338–0.0345
EVA	EVA	0.92/0.95	0.0331–0.0341
Polypropylene	PP	0.90/0.907	0.0324–0.0327
Polybutene-1	PB	0.905/0.920	0.0325–0.0331
Polyisobutylene	PIB	0.91/0.93	0.0327–0.0334
Poly-4-methylpent-1-ene	PMP	0.83	0.0298
Ionomers	—	0.94	0.0338
Rigid PVC	PVC-U	1.38/1.55	0.0496–0.0557
Plasticized PVC	PVC-P	1.16/1.35	0.0417–0.0486
Polystyrene	PS	1.05	0.0378
Styrene/acrylonitrile copolymer	SAN	1.08	0.0392
Styrene/polybutadiene graft polymer	SB	1.05	0.0378
Acrylonitrile/polybut./styrene graft polymer	ABS	1.04/1.06	0.0374–0.0381
AN/AN elastomers/styrene graft polymer	ASA	1.04	0.0374
Polymethylmethacrylate	PMMA	1.17/1.20	0.0421–0.0431
Polyvinylcarbazole	PVK	1.19	0.0428
Polyacetal	POM	1.41/1.42	0.0507–0.0511
Polytetrafluoroethylene	PTFE	2.15/2.20	0.0774–0.0791
Tetrafluoroethylene/hexafluoropropylene copolymer	FEP	2.12/2.17	0.0763–0.0781
Polytrifluorochloroethylene	PCTFE	2.10/2.12	0.0755–0.0762
Ethylene/tetrafluoroethylene	E/TFE	1.7	0.0611
Polyamide 6	PA 6	1.13	0.0406
Polyamide 66	PA 66	1.14	0.0410
Polyamide 11	PA 11	1.04	0.0374
Polyamide 12	PA 12	1.02	0.0367
Polyamide 6-3-T	PA-6-3-T	1.12	0.0403
Polycarbonate	PC	1.2	0.0432
Polyethyleneterephthalate	PET	1.37	0.0492
Polybutyleneterephthalate	PBT	1.31	0.0471
Polyphenyleneether modified	PPE	1.06	0.0381
Polysulfone	PSU	1.24	0.0446
Polyphenylenesulfide	PPS	1.34	0.0483
Polyarylsulfone	PAS	1.36	0.0490
Polyethersulfone	PES	1.37	0.0492
Polyarylether	PAE	1.14	0.0411
Phenol/formaldehyde, grade 31	PF	1.4	0.0504
Urea/formaldehyde, grade 131	UF	1.5	0.0540
Melamine/formaldehyde, grade 152	MF	1.5	0.0540
Unsaturated polyester resin, grade 802	UP	2.0	0.0720
Polydiallylphthalate (GF) molding compound	PDAP	1.51/1.78	0.0543–0.0640
Silicone resin molding compound	SI	1.8/1.9	0.0648–0.0684
Polyimide molding	PI	1.43	0.0515
Epoxy resin, grade 891	EP	1.9	0.0683
Polyurethane casting resin	PU	1.05	0.0378
Thermoplastic PU-elastomers	PU	1.20	0.0432
Linear polyurethane (U ₅₀)	PU	1.21	0.0435
Vulcanized fiber	VF	1.1/1.45	0.0396–0.0522
Celluloseacetate, grade 432	CA	1.30	0.0468
Cellulosepropionate	CP	1.19/1.23	0.0429–0.0452
Celluloseacetobutyrate, grade 413	CAB	1.18	0.0425

Optical properties		Water absorption	
Refractive index n _D ²⁰	Transparency	mg (4 d)	% (24 h)
1.51	transparent	<0.01	<0.01
1.53	opaque	<0.01	<0.01
—	transparent/opaque	—	0.05/0.13
1.49	transparent/opaque	<0.01	0.01/0.03
—	opaque	<0.01	<0.02
—	opaque	<0.01	<0.01
1.46	opaque	—	0.01
1.51	transparent	—	0.1/1.4
1.52/1.55	transparent/opaque	3/18	0.04/0.4
—	transparent/opaque	6/30	0.15/0.75
1.59	transparent	—	0.03/0.1
1.57	transparent	—	0.2/0.3
—	opaque	—	0.05/0.6
—	opaque	—	0.2/0.45
—	translucent/opaque	—	—
1.49	transparent	35/45	0.1/0.4
—	opaque	0.5	0.1/0.2
1.48	opaque	20/30	0.22/0.25
1.35	opaque	—	0
1.34	transparent/translucent	—	<0.1
1.43	translucent/opaque	—	0
1.40	transparent/opaque	—	0.03
1.53	translucent/opaque	—	1.3/1.9
1.53	translucent/opaque	—	1.5
1.52	translucent/opaque	—	0.3
—	translucent/opaque	—	0.25
1.53	transparent	—	0.4
1.58	transparent	10	0.16
—	transparent/opaque	18/20	0.30
—	opaque	—	0.08
—	opaque	—	0.06
1.63	transparent/opaque	—	0.02
—	opaque	—	0.02
1.67	opaque	—	1.8
1.65	transparent	—	0.43
—	translucent/opaque	—	0.25
—	opaque	<150	0.3/1.2
—	opaque	<300	0.4/0.8
—	opaque	<250	0.1/0.6
—	opaque	<45	0.03/0.5
—	opaque	—	0.12/0.35
—	opaque	—	0.2
—	opaque	—	0.32
—	opaque	<30	0.05/0.2
—	transparent	—	0.1/0.2
—	translucent/opaque	—	0.7/0.9
—	translucent/opaque	130	—
—	opaque	—	7/9
1.50	transparent	130	6
1.47	transparent	40/60	1.2/2.8
1.47	transparent	40/60	0.9/3.2

(continued on next page)

Table I (cont.) Guide Values of the Physical Properties of Plastics

Polymer	Abbreviation	Density		Thermal properties			
		g/cm ³	lb/in ³	Service temperature			
				max./short time		max./continuous	
				°C	°F	°C	°F
Low density polyethylene	PE-LD	0.914/0.928	0.0329-0.0330	80/90	176/194	60/75	140/167
High density polyethylene	PE-HD	0.94/0.96	0.0338-0.0345	90/120	194/248	70/80	158/176
EVA	EVA	0.92/0.95	0.0331-0.0341	65	149	55	131
Polypropylene	PP	0.90/0.907	0.0324-0.0327	140	284	100	212
Polybutene-1	PB	0.905/0.920	0.0325-0.0331	130	266	90	194
Polyisobutylene	PIB	0.91/0.93	0.0327-0.0334	80	176	65	149
Poly-4-methylpent-1-ene	PMP	0.83	0.0298	180	356	120	248
Ionomers	—	0.94	0.0338	120	248	100	212
Rigid PVC	PVC-U	1.38/1.55	0.0496-0.0557	75/100	167/212	65/85	149/185
Plasticized PVC	PVC-P	1.16/1.35	0.0417-0.0486	55/65	131/149	50/55	122/131
Polystyrene	PS	1.05	0.0378	60/80	140/176	50/70	122/158
Styrene/acrylonitrile copolymer	SAN	1.08	0.0392	95	203	85	185
Styrene/polybutadiene graft	SB	1.05	0.0378	60/80	140/176	50/70	122/158
Acrylonitrile/polybut./styrene graft polymer	ABS	1.04/1.06	0.0374-0.0381	85/100	188/212	75/85	167/185
AN/AN elastomers/styrene graft polymer	ASA	1.04	0.0374	85/90	188/194	70/75	158/167
Polymethylmethacrylate	PMMA	1.17/1.20	0.0421-0.0431	85/100	188/212	65/90	149/194
Polyvinylcarbazole	PVK	1.19	0.0428	170	338	160	320
Polyacetal	POM	1.41/1.42	0.0507-0.0511	110/140	230	90/110	194/230
Polytetrafluoroethylene	PTFE	2.15/2.20	0.0774-0.0791	300	572	250	482
Tetrafluoroethylene hexafluoropropylene copolymer	FEP	2.12/2.17	0.0763-0.0781	250	482	205	401
Polytrifluorochloroethylene	PCTFE	2.10/2.12	0.0755-0.0762	180	356	150	302
Ethylene tetrafluoroethylene	E/TFE	1.7	0.0611	220	428	150	302
Polyamide 6	PA 6	1.13	0.0406	140/180	284/356	80/100	176/212
Polyamide 66	PA 66	1.14	0.0410	170/200	338/392	80/120	176/248
Polyamide 11	PA 11	1.04	0.0374	140/150	284/302	70/80	158/176
Polyamide 12	PA 12	1.02	0.0367	140/150	284/302	70/80	158/176
Polyamide 6-3-T	PA-6-3-T	1.12	0.0403	130/140	266/284	80/100	176/212
Polycarbonate	PC	1.2	0.0432	160	320	135	275
Polyethyleneterephthalate	PET	1.37	0.0492	200	392	100	212
Polybutyleneterephthalate	PBT	1.31	0.0471	165	329	100	212
Polyphenyleneether modified	PPE	1.06	0.0381	150	302	80	176
Polysulfone	PSU	1.24	0.0446	200	392	150	302
Polyphenylsulfide	PPS	1.34	0.0483	300	572	200	392
Polyarylsulfone	PAS	1.36	0.0490	300	572	260	500
Polyethersulfone	PES	1.37	0.0492	260	500	200	392
Polyarylether	PAE	1.14	0.0411	160	320	120	248
Phenol/formaldehyde, grade 31	PF	1.4	0.0504	140	284	110	230
Urea/formaldehyde, grade 131	UF	1.5	0.0540	100	212	70	158
Melamine/formaldehyde, grade 152	MF	1.5	0.0540	120	248	80	176
Unsaturated polyester resin, grade 802	UP	2.0	0.0720	200	392	150	302
Polydiallylphthalate (GF) molding compound	PDAP	1.51/1.78	0.0543-0.0640	190/250	374/482	150/180	302/356
Silicone resin molding compound	SI	1.8/1.9	0.0648-0.0684	250	482	170/180	338/356
Polyimide molding	PI	1.43	0.0515	400	752	260	500
Epoxy resin, grade 891	EP	1.9	0.0683	180	356	130	266
Polyurethane casting resin	PU	1.05	0.0378	100	212	80	176
Thermoplastic PU-elastomers	PU	1.20	0.0432	110	230	80	176
Linear polyurethane (U ₅₀)	PU	1.21	0.0435	80	176	60	140
Vulcanized fiber	VF	1.1/1.45	0.0396-0.0522	180	356	105	221
Celluloseacetate, grade 432	CA	1.30	0.0468	80	176	70	158
Cellulosepropionate	CP	1.19/1.23	0.0429-0.0452	80/120	176/248	60/115	140/239
Celluloseacetobutyrate, grade 413	CAB	1.18	0.0425	80/120	176/248	60/115	140/239

min./continuous		Heat deflection temperature				Coefficient of linear expansion		Thermal conductivity		Specific heat	
		°C		°F		K ⁻¹ · 10 ⁶	in/in/°F 10 ⁻⁶	W/mK	BTU in/ ft ² h°F	kJ/ kgK	BTU/ lb°F
		VSP (Vicat 5 kg)	1.86/ 0.45 N/ mm ²	VSP (Vicat lb)	264/ 66 psi						
°C	°F										
-50	-58	-	35	-	95	250	140	0.32/0.40	2.2/2.8	2.1/2.5	8.8/10.5
-50	-58	60/70	50	140/158	122	200	110	0.38/0.51	2.6/3.5	2.1/2.7	8.8/11.5
-60	-76	-	34/62	-	93/144	160/200	90/110	0.35	2.4	2.3	9.5
0/-30	32/-22	85/100	45/120	185/212	113/248	150	83	0.17/0.22	1.2/1.5	2.0	8.3
0	32	70	60/110	158	140/230	150	83	0.20	1.4	1.8	7.5
-50	-58	-	-	-	-	120	67	0.12/0.20	0.8/1.4	-	-
0	32	-	-	-	-	117	65	0.17	1.2	2.18	9.1
-50	-58	-	38/45	-	100/113	120	67	0.24	1.7	2.20	9.2
-5	21	75/110	60/82	167/230	140/180	70/80	39/45	0.14/0.17	1.0/1.2	0.85/0.9	3.55/3.75
0/-20	32/-4	40	60/82	104	140/180	150/210	83/110	0.15	1.05	0.9/1.8	3.75/7.5
-10	14	78/99	110/80	172/210	230/176	70	39	0.18	1.25	1.3	5.4
-20	-4	-	104/90	-	219/194	80	45	0.18	1.25	1.3	5.4
-20	-4	77/95	104/82	171/203	219/180	70	39	0.18	1.25	1.3	5.4
-40	-40	95/110	80/120	203/230	176/248	60/110	33/61	0.18	1.25	1.3	5.4
-40	-40	92	100/110	198	212/230	80/110	44/61	0.18	1.25	1.3	5.4
-40	-40	70/100	60/100	158/212	140/212	70	39	0.18	1.25	1.47	6.15
-100	-148	180	-	356	-	-	-	0.29	2.0	-	-
-60	-76	160/173	110/170	320/344	230/338	90/110	50/61	0.25/0.30	1.7/2.1	1.46	6.1
-200	-328	-	-121	-	-250	100	56	0.25	1.7	1.0	4.20
-100	-148	-	-70	-	-158	80	45	0.25	1.7	1.12	4.65
-40	-40	-	-126	-	-259	60	33	0.22	1.5	0.9	3.75
-190	-310	-	71/104	-	160/219	40	22	0.23	1.6	0.9	3.75
-30	-22	180	80/190	356	176/374	80	44	0.29	2.0	1.7	7.1
-30	-22	200	105/200	392	221/392	80	44	0.23	1.6	1.7	7.1
-70	-94	175	150/130	347	302/266	130	72	0.23	1.6	1.26	5.25
-70	-94	165	140/150	329	284/302	150	83	0.23	1.6	1.26	5.25
-70	-94	145	140/80	293	284/176	80	45	0.23	1.6	1.6	6.70
-100	-148	138	130/145	280	266/293	60/70	33/39	0.21	1.45	1.17	4.90
-20	-4	188	-	280	-	70	39	0.24	1.65	1.05	4.40
-30	-22	178	50/190	352	122/374	60	33	0.21	1.45	1.30	5.40
-30	-22	148	100/140	298	212/284	60	33	0.23	1.60	1.40	5.85
-100	-148	-	175/180	-	347/356	54	30	0.28	1.95	1.30	5.40
-	-	-	137/-	-	277/-	55	31	0.25	1.70	-	-
-	-	-	-	-	-	47	26	0.16	1.10	-	-
-	-	-	-	-	-	55	31	0.18	1.25	1.10	4.6
-	-	-	150/160	-	302/320	65	36	0.26	1.80	1.46	6.1
-	-	-	150/190	-	302/374	30/50	17/28	0.35	2.40	1.30	5.40
-	-	-	130/-	-	266/-	50/60	28/33	0.40	2.75	1.20	5.0
-	-	-	180/-	-	356/-	50/60	28/33	0.50	3.45	1.20	5.0
-	-	-	230/-	-	446/-	20/40	11/22	0.70	4.85	1.20	5.0
-50	-58	-	220/-	-	428/-	10/35	55/19	0.60	4.15	-	5.0
-50	-58	-	480/-	-	896/-	20/50	11/28	0.3/0.4	2.05/2.75	0.8/0.9	3.35/3.75
-200	-239	-	240/-	-	464/-	50/63	28/35	0.6/0.65	4.15/4.50	-	-
-	-	-	200/-	-	392/-	11/35	6.1/19	0.88	6.1	0.8	3.35
-40	-40	-	90/-	-	194/-	10/20	5.5/11	0.58	4.0	1.76	7.30
-15	3	100	-	-	-	150	83	1.7	1.15	0.5	2.10
-	-	-	212	-	-	210	12	1.8	1.25	0.4	1.65
-30	-22	-	-	-	-	-	-	-	-	-	-
-40	-40	50/63	90/-	122/144	194/-	120	67	0.22	1.50	1.6	6.7
-40	-40	100	73/98	212	163/208	110/130	61/72	0.21	1.45	1.7	7.1
-40	-40	60/75	62/71	140/167	144/160	120	67	0.21	1.45	-	-

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(continued on next page)

Table 1 (cont.) Guide Values of the Physical Properties of Plastics

Polymer	DIN 7728 Bl. 1	Density		Electrical properties	
		g/cm ³	lb/in ³	Volume resistivity Ω cm	Surface resistance Ω
Low density polyethylene	PE-LD	0.914/0.928	0.0329–0.0330	> 10 ¹⁷	10 ¹⁴
High density polyethylene	PE-HD	0.94/0.96	0.0338–0.0345	> 10 ¹⁷	10 ¹⁴
EVA	EVA	0.92/0.95	0.0331–0.0341	< 10 ¹⁵	10 ¹³
Polypropylene	PP	0.90/0.907	0.0324–0.0327	> 10 ¹⁷	10 ¹³
Polybutene-1	PB	0.905/0.920	0.0325–0.0331	> 10 ¹⁷	10 ¹³
Polyisobutylene	PIB	0.91/0.93	0.0327–0.0334	> 10 ¹⁵	10 ¹³
Poly-4-methylpent-1-ene	PMP	0.83	0.0298	> 10 ¹⁶	10 ¹³
Ionomers	—	0.94	0.0338	> 10 ¹⁶	10 ¹³
Rigid PVC	PVC-U	1.38/1.55	0.0496–0.0557	> 10 ¹⁵	10 ¹³
Plasticized PVC	PVC-P	1.16/1.35	0.0417–0.0486	> 10 ¹¹	10 ¹¹
Polystyrene	PS	1.05	0.0378	> 10 ¹⁶	> 10 ¹³
Styrene/acrylonitrile copolymer	SAN	1.08	0.0392	> 10 ¹⁶	> 10 ¹³
Styrene/polybutadiene graft polymer	SB	1.05	0.0378	> 10 ¹⁶	> 10 ¹³
Acrylonitrile/polybut./styrene graft polymer	ABS	1.04/1.06	0.0374–0.0381	> 10 ¹⁵	> 10 ¹³
AN/AN elastomers/styrene graft polymer	ASA	1.04	0.0374	> 10 ¹⁵	> 10 ¹³
Polymethylmethacrylate	PMMA	1.17/1.20	0.0421–0.0431	> 10 ¹⁵	10 ¹⁵
Polyvinylcarbazole	PVK	1.19	0.0428	> 10 ¹⁶	10 ¹⁴
Polyacetal	POM	1.41/1.42	0.0507–0.0511	> 10 ¹⁵	10 ¹³
Polytetrafluoroethylene	PTFE	2.15/2.20	0.0774–0.0791	> 10 ¹⁸	10 ¹⁷
Tetrafluoroethylene/hexafluoropropylene copolymer	FEP	2.12/2.17	0.0763–0.0781	> 10 ¹⁸	10 ¹⁶
Polytrifluorochloroethylene	PCTFE	2.10/2.12	0.0755–0.0762	> 10 ¹⁸	10 ¹⁶
Ethylene/tetrafluoroethylene	E/TFE	1.7	0.0611	> 10 ¹⁶	10 ¹³
Polyamide 6	PA 6	1.13	0.0406	10 ¹²	10 ¹⁰
Polyamide 66	PA 66	1.14	0.0410	10 ¹²	10 ¹⁰
Polyamide 11	PA 11	1.04	0.0374	10 ¹³	10 ¹¹
Polyamide 12	PA 12	1.02	0.0367	10 ¹³	10 ¹¹
Polyamide 6-3-T	PA-6-3-T	1.12	0.0403	10 ¹¹	10 ¹⁰
Polycarbonate	PC	1.2	0.0432	> 10 ¹⁷	> 10 ¹⁵
Polyethyleneterephthalate	PET	1.37	0.0492	10 ¹⁶	10 ¹⁶
Polybutyleneterephthalate	PBT	1.31	0.0471	10 ¹⁶	10 ¹³
Polyphenyleneether modified	PPE	1.06	0.0381	10 ¹⁶	10 ¹⁴
Polysulfone	PSU	1.24	0.0446	> 10 ¹⁶	—
Polyphenylenesulfide	PPS	1.34	0.0483	> 10 ¹⁶	—
Polyarylsulfone	PAS	1.36	0.0490	> 10 ¹⁶	—
Polyethersulfone	PES	1.37	0.0492	10 ¹⁷	—
Polyarylether	PAE	1.14	0.0411	> 10 ¹⁰	—
Phenol/formaldehyde, grade 31	PF	1.4	0.0504	10 ¹¹	> 10 ⁸
Urea/formaldehyde, grade 131	UF	1.5	0.0540	10 ¹¹	> 10 ¹⁰
Melamine/formaldehyde, grade 152	MF	1.5	0.0540	11 ¹¹	> 10 ⁸
Unsaturated polyester resin, grade 802	UP	2.0	0.0720	> 10 ¹²	> 10 ¹⁰
Polydiallylphthalate (GF) molding compound	PDAP	1.51/1.78	0.0543–0.0640	10 ¹³ /10 ¹⁶	10 ¹³
Silicone resin molding compound	SI	1.8/1.9	0.0648–0.0684	10 ¹⁴	10 ¹²
Polyimide molding	PI	1.43	0.0515	> 10 ¹⁶	> 10 ¹⁵
Epoxy resin, grade 891	EP	1.9	0.0683	> 10 ¹⁴	> 10 ¹²
Polyurethane casting resin	PU	1.05	0.0378	10 ¹⁶	10 ¹⁴
Thermoplastic PU-elastomers	PU	1.20	0.0432	10 ¹²	10 ¹¹
Linear polyurethane (U ₅₀)	PU	1.21	0.0435	10 ¹³	10 ¹²
Vulcanized fiber	VF	1.1/1.45	0.0396–0.0522	10 ¹⁰	10 ⁸
Celluloseacetate, grade 432	CA	1.30	0.0468	10 ¹³	10 ¹²
Cellulosepropionate	CP	1.19/1.23	0.0429–0.0452	10 ¹⁶	10 ¹⁴
Celluloseacetobutyrate, grade 413	CAB	1.18	0.0425	10 ¹⁶	10 ¹⁴

Dielectric constant		Dissipation (power) factor tan δ		Dielectric strength		Tracking resistance		
50 Hz	10 ⁶ Hz	50 Hz	10 ⁶ Hz	kV/25 μm	kV/cm	KA	KB	KC
2.29	2.28	1.5 · 10 ⁻⁴	0.8 · 10 ⁻⁴	> 700	—	3b	> 600	> 600
2.35	2.34	2.4 · 10 ⁻⁴	2.0 · 10 ⁻⁴	> 700	—	3c	> 600	> 600
2.5/3.2	2.6/3.2	0.003/0.02	0.003/0.05	—	620/780	—	—	—
2.27	2.25	< 4 · 10 ⁻⁴	< 5 · 10 ⁻⁴	800	500/650	3c	> 600	> 600
2.5	2.2	7 · 10 ⁻⁴	6 · 10 ⁻⁴	700	—	3c	> 600	> 600
2.3	—	0.0004	—	230	—	3c	> 600	> 600
2.12	2.12	7 · 10 ⁻⁵	3 · 10 ⁻⁵	280	700	3c	> 600	> 600
3.5	3.0	0.011	0.015	200/400	350/500	2/3b	600	600
4/8	4/4.5	0.08	0.12	150/300	300/400	—	—	—
2.5	2.5	1/4 · 10 ⁻⁴	0.5/4 · 10 ⁻⁴	500	300/700	1/2	140	150/250
2.6/3.4	2.6/3.1	6/8 · 10 ⁻³	7/10 · 10 ⁻³	500	400/500	1/2	160	150/260
2.4/4.7	2.4/3.8	4/20 · 10 ⁻⁴	4/20 · 10 ⁻⁴	500	300/600	2	> 600	> 600
2.4/5	2.4/3.8	3/8 · 10 ⁻³	2/15 · 10 ⁻³	400	350/500	3a	> 600	> 600
3/4	3/3.5	0.02/0.05	0.02/0.03	350	360/400	3a	> 600	> 600
3.3/3.9	2.2/3.2	0.04/0.06	0.004/0.04	300	400/500	3c	> 600	> 600
—	3	6/10 · 10 ⁻⁴	6/10 · 10 ⁻⁴	500	—	3b	> 600	> 600
3.7	3.7	0.005	0.005	700	380/500	3b	> 600	> 600
< 2.1	< 2.1	< 2 · 10 ⁻⁴	< 2 · 10 ⁻⁴	500	480	3c	> 600	> 600
2.1	2.1	< 2 · 10 ⁻⁴	< 7 · 10 ⁻⁴	500	550	3c	> 600	> 600
2.3/2.8	2.3/2.5	1 · 10 ⁻³	2 · 10 ⁻²	500	550	3c	> 600	> 600
2.6	2.6	8 · 10 ⁻⁴	5 · 10 ⁻³	380	400	3c	> 600	> 600
3.8	3.4	0.01	0.03	350	400	3b	> 600	> 600
8.0	4.0	0.14	0.08	400	600	3b	> 600	> 600
3.7	3.5	0.06	0.04	300	425	3b	> 600	> 600
4.2	3.1	0.04	0.03	300	450	3b	> 600	> 600
4.0	3.0	0.03	0.04	250	350	3b	> 600	> 600
3.0	2.9	7 · 10 ⁻⁴	1 · 10 ⁻²	350	380	1	120/160	260/300
4.0	4.0	2 · 10 ⁻³	2 · 10 ⁻²	500	420	2	—	—
3.0	3.0	2 · 10 ⁻³	2 · 10 ⁻²	500	420	3b	420	380
2.6	2.6	4 · 10 ⁻⁴	9 · 10 ⁻⁴	500	450	1	300	300
3.1	3.0	8 · 10 ⁻⁴	3 · 10 ⁻³	—	425	1	175	175
3.1	3.2	4 · 10 ⁻⁴	7 · 10 ⁻⁴	—	595	—	—	—
3.9	3.7	3 · 10 ⁻³	13 · 10 ⁻³	—	350	—	—	—
3.5	3.5	1 · 10 ⁻³	6 · 10 ⁻³	—	400	—	—	—
3.14	3.10	6 · 10 ⁻³	7 · 10 ⁻³	—	430	—	—	—
6	4.5	0.1	0.03	50/100	300/400	1	140/180	125/175
8	7	0.04	0.3	80/150	300/400	3a	> 400	> 600
9	8	0.06	0.03	80/150	290/300	3b	> 500	> 600
6	5	0.04	0.02	120	250/530	3c	> 600	> 600
5.2	4	0.04	0.03	—	400	3c	> 600	> 600
4	3.5	0.03	0.02	—	200/400	3c	> 600	> 600
3.5	3.4	2 · 10 ⁻³	5 · 10 ⁻³	—	560	1	> 300	> 380
3.5/5	3.5/5	0.001	0.01	—	300/400	3c	> 300	200/600
3.6	3.4	0.05	0.05	—	240	3c	—	—
6.5	5.6	0.03	0.06	—	300/600	3a	> 600	> 600
5.8	4.0	0.12	0.07	330	—	—	—	—
—	—	0.08	—	70/180	—	—	—	—
5.8	4.6	0.02	0.03	320	400	3a	> 600	> 600
4.2	3.7	0.01	0.03	350	400	3a	> 600	> 600
3.7	3.5	0.006	0.021	380	400	3a	> 600	> 600

Table II Permeability of Films Made from Various Polymers

Polymer	Temperature		Film thickness	Water vapor	N ₂	Air	O ₂	CO ₂	H ₂	Ar	He
	SI	US									
	°C	°F	μm ¹⁾	g/cm ² day	cm ³ /m ² day bar						
PE-LD	23	73	100	1	700	1100	2000	10000	8000	—	—
PE-HD (ρ = 0.95 g/cm ³ , unstretched)	25	77	40	0.9	525	754	1890	7150	6000	—	—
	30	86	40	1.7	720	960	2270	8600	7600	—	—
	40	104	40	3.5	1220	1660	3560	13100	11400	—	—
	50	122	40	8.1	2140	2650	5650	19500	16800	—	—
PE-HD (ρ = 0.95 g/cm ³ , stretched)	25	77	40	1.0	430	680	1210	5900	5000	—	—
	30	86	40	1.6	560	830	1530	7200	6000	—	—
	40	104	40	4.3	1050	1490	2650	11200	9400	—	—
	50	122	40	10.5	1870	2670	4650	18100	14800	—	—
E/VA copolymer, VAC 20%	23	73	100	455	1400	—	4000	17000	—	—	—
Polypropylene (unstretched)	25	77	40	2.1	430	700	1900	6100	17700	1480	19200
	30	86	40	3.2	600	960	2500	8400	18200	2100	21700
	40	104	40	7.4	1280	1820	5100	14800	28100	4100	29800
	50	122	40	19.0	2800	3600	9200	27300	46600	8000	43500
Polypropylene (stretched)	25	77	40	0.81	200	350	1000	3300	6700	—	7300
	30	86	40	1.2	260	480	1200	3900	8200	—	8500
	40	104	40	3.3	560	940	2300	7050	12300	—	12100
	50	122	40	8.4	1200	1850	4150	13200	19800	—	17800
PVC-U (unstretched)	20	68	40	7.6	12	28	87	200	—	—	—
PVC-U (stretched)	20	68	40	4.4	13	13	43	110	—	—	—
PVC-P	20	68	40	20	350	550	1500	8500	—	—	—
Polyvinylidenechloride	25	77	25	0.1/0.2	1.8/2.3	5/10	1.7/11	60/700	630/1400	—	—
Polystyrene (stretched)	25	77	50	14.0	27	80	235	800	1260	—	—
	20	68	40	2.5	10	16	50	96	420	—	—
PFEP copolymers	40	104	25	2.0	375	—	3000	6500	2000	—	—
	40	104	25	0.38/0.85	39	—	110/230	250/620	3400/5200	—	—
E/TFE copolymers	23	73	25	0.6	470	—	1560	3800	—	—	—
	23	73	25	9.0	150	—	39.0	1700	—	—	—
E/CTFE copolymers	23	73	25	50.0	3.8	—	4.7	170	900	—	—
	23	73	25	50.0	3.8	—	4.7	170	900	—	—
Polyamide 6	25	77	25	80/110	14	—	40	200	1500	—	—
	25	77	25	15/30	11	—	80	140	—	—	—
	25	77	25	1.5/4.0	50	—	540	2400	5000	—	—
	25	77	25	0.35	200/280	—	800/1400	2600/5300	—	—	—
Polyamide 66	25	77	25	15/30	11	—	80	140	—	—	—
Polyamide 11	25	77	25	1.5/4.0	50	—	540	2400	5000	—	—
Polyamide 12	25	77	25	0.35	200/280	—	800/1400	2600/5300	—	—	—
Polycarbonate	23	73	25	4	680	—	4000	14500	22000	—	—
Polyethyleneterephthalate (stretched)	23	73	25	0.6	9/15	—	80/110	200/340	1500	—	—
Polysulfone	23	73	25	6	630	—	3600	15000	28000	—	—
PU elastomers	23	73	25	13/25	550/1600	—	1000/4500	6000/22000	—	—	—
Polyimide	23	73	25	25	94	—	390	700	3800	—	—
Celluloseacetate	25	77	25	150/600	470/630	—	1800/2300	13000/15000	14000	—	—
Celluloseacetobutyrate	25	77	25	460/600	3800	—	15000	94000	—	—	—

¹⁾ 1 μm = 0.0394 mil.

Subject Index

A

ABS 40
acrylonitrile-butadiene-styrene (ABS) 14
addition polymerization 7, 167
additives 15
air ring 146
alternating 14
amorphous thermoplastic 11
annual polymer production 3
antistatic agents 16
approach or land 82

B

Bagley 62
banbury mixer, 105
barrier flights 79
biaxial molecular orientation 151
biaxial stretching 145
bipolymer 14
block 14
blow molding 148
blowing agents 17
branching 10
break up time 103
Brinkman number, Br 52

C

calendering 159
capillary number 102
capillary visco-meter 60
carbon black 99
cast film extrusion 143
Castro-Macosko curing model 170
cavity transfer mixing section 107
check valve 127
chemical foaming 175
clamping force 122
clamping unit 127
closed discharge 72
co-injection molding 131
co-rotating twin screw extruder 111
coat-hanger sheeting die 82
cokneader 110
collapsing rolls 146
compression molding 171
computer simulation 132
condensation polymerization 9, 167
cone-and-plate rheometer 63
consistency index 49
continuity equation 207
cooling system 128
cooling time 119
copolymers 14
Couette flow 51
counter-rotating twin screw extruder 112

CRD mixing section 108
creep rupture 29
creep test 26
critical capillary number 102
cross-head tubing die 84
cross-linking 13
crosslinked elastomers 13
curing reaction models 169
curing thermoset 56
curtain coating 163

D

Deborah number 54
degradation 120
degree of cure 56
die lips 82
differential scanning calorimeter (DSC) 168
dioctylphthalate 15
dip coating 163
disperse static mixer 110
dispersed melting 110
dispersive mixing 99
distributive mixing 95
drop break-up 103
dynamic fatigue, 39
dynamic mechanical tests 29

E

ejector system 128
elastic shear modulus 32
energy equation 207
equation of motion 208
Erwin's ideal mixer 99
ethylene 8
extrudate swell 53
extrudate swell 54
extruder dimensions 70
extrusion blow molding 149
extrusion die 82

F

fatigue 39
fiber orientation 132, 172
fiber reinforced polymer (FRP) 32
fiber spinning 141
filled polymers 25
fillers 16
film blowing 145
flash 120
flex lips 82
flow number 101
foaming 175
forward roll coating 164
freezing line 145

G

gate 128
 glass mat reinforced thermoplastic 171
 glass transition temperature 11, 13
 graft copolymers 14
 grooved feed extruders 73
 grooved feed section 73

H

Hagen-Poiseuille flow 50
 Halpin and Tsai 34
 Hele-Shaw model 132
 high impact polystyrene (PS-HI) 14
 hydraulic clamping unit 128

I

impact strength 36
 injection blow molding 151
 injection molding 117, 132
 injection molding cycle 118
 injection molding machine 117
 injection pressure 122
 internal batch mixer. 105
 isochronous 27
 isometric creep plots 27

K

Kenics static mixer 109
 knife coating 163

L

lamellar crystal 12
 laminar mixing 95
 LDPE 48, 53
 long fiber composites 33
 loss modulus 32
 loss tangent 32
 low density polyethylene 115

M

Maddock 108
 manifold 82
 mechanical properties 19
 melt film 76
 melt flow indexer 60
 melt fracture 54
 melt pool 76
 melting or transition zone 76
 melting temperature. 13
 metering zone 80
 mixing devices 104
 mold cavity 128
 molding diagram 120
 molecular weight 9
 morphology development 111

morphology development in polymer blends 95
 multi-color injection molding 131
 multi-component injection molding 131

N

Newtonian plateau 48
 nitrogen compounds 16
 non-isothermal flows 52
 normal stress coefficients 52
 normal stresses 52
 nozzle 127
 nucleating agents 17

O

open discharge. 72
 optimal orientation 99

P

parison 149
 parison programming 149
 particulate solid agglomerates 99
 Paul Troester Maschinenfabrik 67
 phenol-formaldehyde 13
 phenolic 13
 physical foaming 175
 pin barrel extruder 107
 pin mixing section 106
 pinch-off 152
 pineapple mixing section 107
 plasticating single screw extruder 69
 plasticating unit 126
 plasticizers 15
 plug-assist thermoforming 153
 polyamide 9
 polyethylene 8, 207
 polyisobutylene 19
 polypropylene 30, 113
 polypropylene copolymer 26
 polystyrene 114
 power law index. 49
 power-law model 48
 pressure flow 50
 properties 6
 pumping systems 67
 pVT diagram 120

Q

QSM-extruder 106

R

random 14
 reactive polymers 167
 reduced first normal stress difference 53
 reduced viscosity 48
 reinforced polymers 32
 residual stress 125, 174

reverse draw thermoforming 153
 rheology 47
 rheology of curing chermosets 56
 ribbing in roll coating 165
 roll coating 163
 rotational molding 176
 rubber 1
 rubber compound 99
 rubber elasticity 24

S

S-N curves 39
 scaling 181
 screen pack, 141
 screw characteristic curves 71
 self-cleaning 111
 semi-crystalline thermoplastic 12
 shark skin 54
 shear thinning behavior 48
 sheet molding compound 171
 sheeting die 82
 short fiber composites 33
 short shot 120
 short-term tensile test 22
 shrinkage 174
 simple shear flow 49
 simplified flows 49
 single screw extruder 68
 sink marks 125
 sinusoidal oscillatory test 31
 slide coating 163
 sliding plate rheometer 47
 smooth barrel 71
 solid bed 76
 solids conveying zone 72
 song of Deborah 55
 sperulitic structure 12
 spider die 84
 spinneret 141
 spiral die 85
 sprue and runner system 128
 spurt flow 54
 stability analysis of spinning 142
 stability analysis of film casting 143
 stabilizers 16
 static fatigue 38
 stick-slip 54
 storage modulus 32
 stress relaxation 19
 structure of polymers 7
 stuffing machine 117
 styrene-butadiene-rubber (SBR) 14
 suspension rheology 57

T

Tadmor model 78
 terpolymer 14
 thermal fatigue. 40

thermoforming 152
 thermosets 13
 time-temperature superposition 20
 toggle mechanism 127
 tubular die 84
 twin screw extruders 69, 111

U

U.S. polymer production 4
 Union Carbide mixing section 108
 unsaturated 35
 unsaturated polyester 168
 upper bound 99

V

vinyl ester 56
 viscoelastic flow models 58
 viscoelasticity 19
 viscosity curves 114
 viscous heating 52
 volume-specific energy to fracture 37

W

warpage 125, 174
 weathering 40
 Weissenberg-Rabinowitsch equation 62
 wind-up station 159
 wire coating 163
 WLF equation 21



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This book ties material behavior to the various processing techniques applied in the manufacturing of plastic parts. It is written at two clearly distinguished levels: an introductory level for students and engineers unfamiliar with polymer processing, and a more advanced level offering in-depth material for those readers with some background in the polymer processing field.

Numerous examples and problems together with laboratory exercises for all major processes at the end of the book emphasize the practical approach of this text. Both engineering students and practicing engineers will find this unique text most helpful in their attempt to acquire solid knowledge in polymer processing.

Contents:

- Introduction to Polymers
- Mechanical Behavior of Polymers
- Rheology of Polymer Melts
- Extrusion
- Mixing
- Injection Molding
- Secondary Shaping
- Other Important Polymer Processes
- Extrusion Laboratory
- Injection Molding Laboratory
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ISBN 1-56990-262-3
Hanser Gardner Publications
<http://www.hansergardner.com>

ISBN 3-446-19571-8
Carl Hanser Verlag
<http://www.hanser.de>



EG_000216634