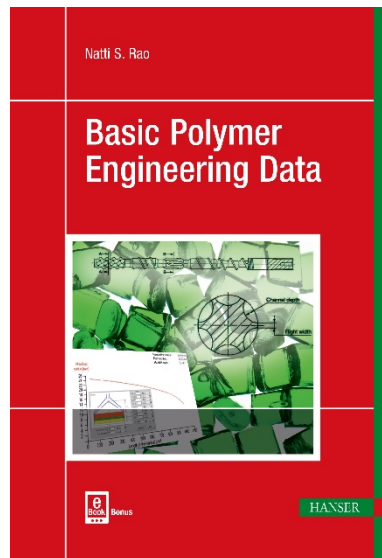


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## Sample Pages

### Basic Polymer Engineering Data

Natti S. Rao

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# Preface

Mechanical, thermal, and rheological properties of polymers form the basic group of property values required for designing polymer machinery. In addition, knowledge of the properties of the resin, such as stock temperature of the melt, is necessary for optimizing the process. Furthermore, while designing a plastic part, performance properties of the resin, depending on the application, are to be considered. Examples of which are flammability, weather resistance, and optical properties, to name a few. Hence, a variety of property values is needed to accomplish machine design, part design, and process optimization.

The bulk of polymer machinery is comprised of extruders and injection molding machines. Their designs can be accomplished empirically by trial and error procedures based on experiments. However, these methods are costly and time-consuming and not always feasible if one has to work with large units like a high speed blown film line or a sheet making unit of a thermoforming plant.

As a result, the use of software based on numerical analysis of the processes occurring in these machine elements has found more applications and become a state-of-the-art design tool. The property data required to perform design calculations using software exists in databanks, which are available on the market. However, for a number of practical applications, these databanks are too extensive to justify their use; for example, to obtain a quick estimate of the dimensions of an extrusion die or the cooling of a part in an injection molding die.

The intent of this book, first of all, is to create an easy to use quick reference that covers basic design data on resin, machine, part, and process, and second, to show how this data can be applied to solve practical problems. With this aim in mind, numerous examples are given to illustrate the use of this data. The calculations involved in these examples can be easily handled with the help of handheld calculators.

Chapters 1 to 5 deal with the description of physical properties—mechanical, thermal, rheological, electrical, and optical—of polymers and principles of their measurement. In Chapter 6 the effect of external influences on the performance of polymers is treated. General property data for different materials such as liquid crystal



polymers, structural foams, thermosetting resins, and reinforced plastics are given at the end of this chapter.

In Chapter 7 the processing properties and machine related data are presented for continuous extrusion processes; namely, blown film, pipe, and flat film extrusion. Resin and machine parameters for thermoforming and compounding have also been included in this chapter.

Chapter 8 deals with blow molding and the influence of resin and machine variables on different kinds of blow molding processes. Finally, Chapter 9 covers resin-dependent and machine-related parameters concerning the injection molding process.

Machine element design, covered in Chapters 7 to 9, includes screw design for extruders and injection molding machines, die design for extruders, mold design for molding and forming operations, and downstream equipment for extrusion. Wherever appropriate, the properties and machine related parameters are described by mathematical formulas that are, as already mentioned, illustrated by worked-out examples. The solution procedure used in these examples describes the application of polymer data to solve practical problems. On the basis of this approach, the importance of polymer data in dealing with design and process optimization is explained.

Thanks are due to Dr. Benjamin Dietrich of The Karlsruhe Institute of Technology for his cooperation in preparing the manuscript, and to Prof. Stephen Orroth of the University of Massachusetts at Lowell, for his fruitful suggestions.

I am extremely grateful to Dr. Mark Smith of Hanser for his careful review of the manuscript and corrections needed to attain compatibility with the printing requirements. Thanks are also due to Cheryl Hamilton for her great help in editing the text. The careful proofreading and various suggestions for improving the manuscript by Julia Diaz, associate editor of Hanser, are also thankfully acknowledged.

*Natti S. Rao, Ph. D.*

# 2

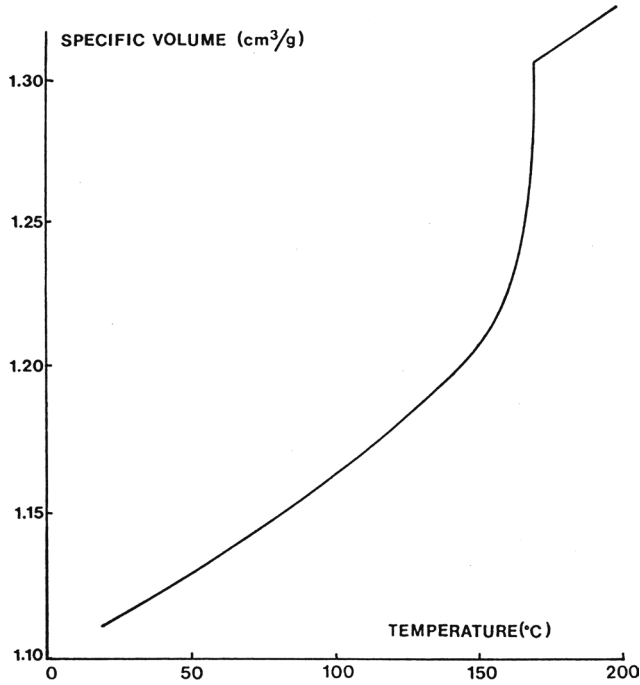
## Thermal Properties of Solid and Molten Polymers

In addition to the mechanical and melt flow properties, thermodynamic data of polymers are necessary for optimizing various heating and cooling processes which occur in plastics processing operations.

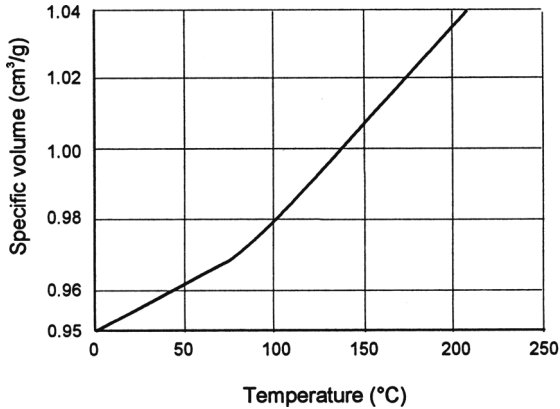
In design work, the thermal properties are often required as functions of temperature and pressure [2]. As the measured data cannot always be predicted by physical relationships accurately enough, regression equations are used to fit the data for use in design calculations.

### ■ 2.1 Specific Volume

The volume-temperature relationship as a function of pressure is shown for a semicrystalline PP in Fig. 2.1 [1], and for an amorphous PS in Fig. 2.2 [1]. The  $p$ - $v$ - $T$  diagrams are needed in many applications; for example, to estimate the shrinkage of plastics parts in injection molding [19]. Data on  $p$ - $v$ - $T$  relationships for a number of polymers are presented in the VDMA-handbook [8].



**Figure 2.1** Specific volume vs. temperature for a semicrystalline polymer (PP) [1]



**Figure 2.2** Specific volume vs. temperature for an amorphous polymer (PS) [1]

According to the Spencer-Gilmore equation, which is similar to the van der Waals equation of state for real gases, the relationship between pressure  $p$ , specific volume  $v$ , and temperature  $T$  of a polymer can be written as

$$(v - b^*)(p + p^*) = \frac{RT}{W} \quad (2.1)$$

In this equation  $b^*$  is the specific individual volume of the macromolecule,  $p^*$  the cohesion pressure,  $W$  the molecular weight of the monomer, and  $R$  the universal gas constant [9].

The values  $p^*$  and  $b^*$  can be determined from  $p$ - $v$ - $T$  diagrams by means of regression analysis. Spencer and Gilmore and other workers evaluated these constants from measurements for the polymers listed in Table 2.1 [9, 18].

**Table 2.1** Constants for the Equation of State [9]

Material	$W$ g/mol	$p^*$ atm	$b^*$ cm <sup>3</sup> /g
PE-LD	28.1	3240	0.875
PP	41.0	1600	0.620
PS	104	1840	0.822
PC	56.1	3135	0.669
PA 610	111	10768	0.9064
PMMA	100	1840	0.822
PET	37.0	4275	0.574
PBT	113.2	2239	0.712

**Example:**

Following values are given for a PE-LD:

$$W = 28.1 \text{ g/mol}$$

$$b^* = 0.875 \text{ cm}^3/\text{g}$$

$$p^* = 3240 \text{ atm}$$

Calculate the specific volume at  $T = 190 \text{ }^\circ\text{C}$  and  $p = 1 \text{ bar}$

**Solution:**

Using Eq. 2.1 and the conversion factors to obtain the volume  $v$  in cm<sup>3</sup>/g, we obtain

$$v = \frac{10 \cdot 8.314 \cdot (273 + 190)}{28.1 \cdot 3240 \cdot 99 \cdot 1.013} + 0.875 = 1.292 \text{ cm}^3/\text{g}$$

The density  $\rho$  is the reciprocal value of specific volume so that

$$\rho = \frac{1}{v}$$

The  $p$ - $v$ - $T$  data can also be fitted by a polynomial of the form

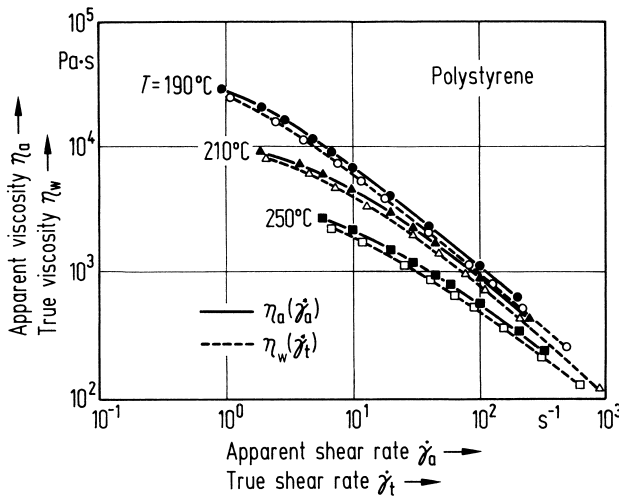
$$v = A(0)_v + A(1)_v \cdot p + A(2)_v \cdot T + A(3)_v \cdot T \cdot p \quad (2.2)$$

### 3.2.6 True Viscosity

The true viscosity  $\eta_w$  is given by

$$\eta_w = \frac{\tau}{\dot{\gamma}_t} \quad (3.11)$$

In Fig. 3.11, the true and apparent viscosities are plotted as functions of the corresponding shear rates at different temperatures for polystyrene. As can be seen, the apparent viscosity function is a good approximation for engineering calculations.



**Figure 3.11** True and apparent viscosity functions of a polystyrene at different temperatures [4]

## 3.3 Rheological Models

Various fluid models have been developed to calculate the apparent shear viscosity  $\eta_a$  [2]. The following sections deal with an important few of these relationships, which are frequently used in design calculations.

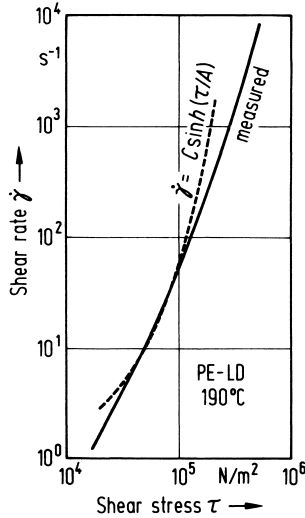
### 3.3.1 Hyperbolic Function of Eyring and Prandtl

The relation between shear rate  $\dot{\gamma}_a$  and shear stress  $\tau$  according to the fluid model of Eyring [19] and Prandtl [20] can be written as

$$\dot{\gamma}_a = -C \sinh(\tau/A) \quad (3.12)$$

where  $C$  and  $A$  are temperature-dependent material constants.

The evaluation of the constants  $C$  and  $A$  for the flow curve of PE-LD at  $190^\circ\text{C}$  in Fig. 3.12 leads to  $C = 4\text{ s}^{-1}$  and  $A = 3 \cdot 10^4\text{ N/m}^2$ . It can be seen from Fig. 3.12 that the hyperbolic function of Prandtl and Eyring holds well at low shear rates.



**Figure 3.12** Comparison between measurements and values calculated with Eq. 3.12 [2]

### 3.3.2 Power Law of Ostwald and de Waele

The power law of Ostwald [21] and de Waele [22] is easy to use, hence, it is widely employed in design work [5]. This relation can be expressed as

$$\dot{\gamma}_a = K \tau^n \quad (3.13)$$

or

$$\dot{\gamma}_a = K \left| \tau^{n-1} \right| \tau \quad (3.14)$$

where  $K$  denotes a factor of proportionality and  $n$  the power law exponent.

Another form of power law often used is

$$\tau_a = K_R \dot{\gamma}_a^{n_R} \quad (3.15)$$

or

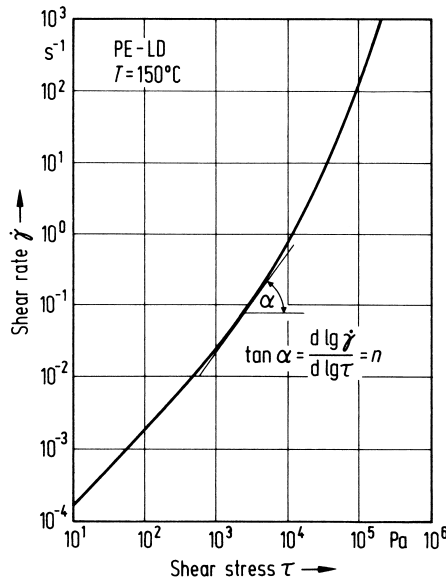
$$\tau_a = K_R \left| \dot{\gamma}_a^{n_R-1} \right| \dot{\gamma}_a \quad (3.16)$$

In this case,  $n_R$  is the reciprocal of  $n$  and  $K_R = K^{-n_R}$ .

From Eq. 3.13, the exponent  $n$  can be expressed as

$$n = \frac{d \lg \dot{\gamma}_a}{d \lg \tau} \quad (3.17)$$

As shown in Fig. 3.13, in a double log-plot, the exponent  $n$  represents the local gradient of the curve  $\dot{\gamma}_a$  vs.  $\tau$ .



**Figure 3.13** Determination of the power law exponent  $n$  in the Eq. 3.13

Furthermore

$$\frac{1}{n} = \frac{d \lg \tau}{d \lg \dot{\gamma}_a} = \frac{d \lg \eta_a + d \lg \dot{\gamma}_a}{d \lg \dot{\gamma}_a} = \frac{d \lg \eta_a}{d \lg \dot{\gamma}_a} + 1 \quad (3.18)$$

The values of  $K$  and  $n$  determined from the flow curve of PE-LD at 190 °C, shown in Fig. 3.14, were found to be  $K = 1.06 \cdot 10^{-11}$  and  $n = 2.57$ .

As can be seen from Fig. 3.14, the power law fits the measured values much better than the hyperbolic function of Eyring [19] and Prandtl [20]. The deviation between the power law and experiment is a result of the assumption that the exponent  $n$  is constant throughout the range of shear rates considered, whereas  $n$  actually varies with the shear rate. The power law can be extended to consider the effect of temperature on viscosity as follows:

$$\eta_a = K_{OR} \cdot \exp(-\beta \cdot T) \cdot \dot{\gamma}_a^{n_R-1} \quad (3.19)$$

where  $K_{OR}$  = consistency index  
 $\beta$  = temperature coefficient  
 $T$  = temperature of melt

# 5

## Optical Properties of Solid Polymers

### ■ 5.1 Light Transmission

The intensity of light incident on the surface of a plastic is reduced as the light enters the plastic because some light is always reflected away from the surface. The intensity of light entering the plastic is further reduced as the light passes through the plastic since some light is absorbed, or scattered, by the plastic. The luminous transmittance is defined as the percentage of incident light that is transmitted through the plastic. For comparison purposes the exact test parameters are documented in ASTM D 1003. Some typical light transmission values for the most common optical plastics are presented in Table 5.1. Light transmission is a measurement of the transparency of a plastic.

**Table 5.1** Light Transmission or Luminous Transmittance of Some Common Optical Plastics

Material	Luminous transmittance D 1003
ABS	85
PC	89
PMMA	92
PMMA/PS	90
PS	88
SAN	88

### ■ 5.2 Haze

Haze is defined as the percentage of transmitted light which deviates from the incident light beam by more than 2.5 degrees. Its measurement is also defined by ASTM D 1003. Some typical haze values are presented in Table 5.2 for the most common optical plastics. Haze is a measure of the clarity of a plastic.



**Table 5.2** Haze of Some Common Optical Plastics

Material	Haze
ABS	10
PC	1 – 3
PMMA	1 – 8
PMMA/PS	2
PS	3
SAN	3

## ■ 5.3 Refractive Index

The refractive index  $n$  of an isotropic material is defined as the ratio of the speed of light in the material  $v$  to the speed of light in vacuum  $c$ , that is,

$$n = v/c$$

The speed of light in vacuum is 300,000 km/s. The refractive index decreases as the wavelength of the light increases. Therefore, the refractive index is measured and reported at a number of standard wavelengths, or atomic emission spectra (AES) lines, as indicated in Table 5.3.

**Table 5.3** Refractive Indices as Functions of Wavelength

AES line	Wavelength	PMMA	PS	PC
F	486 nm	1.497	1.607	1.593
D	589 nm	1.491	1.590	1.586
C	651 nm	1.489	1.584	1.576

The refractive index is usually measured using an Abbe refractometer according to ASTM D542. The Abbe refractometer also measures the dispersions, which is required for lens design. An extensive list of refractive indices is provided in Table 5.4. Since the speed of light in the polymer  $v$  is a function of the density, polymers which exhibit a range of densities also exhibit a range of refractive indices. Since density is a function of crystallinity, the refractive index is dependent on whether the polymer is amorphous or crystalline, and on its degree of crystallinity. Since density is also a function of temperature, decreasing as temperature increases, the refractive index also decreases with increasing temperature.

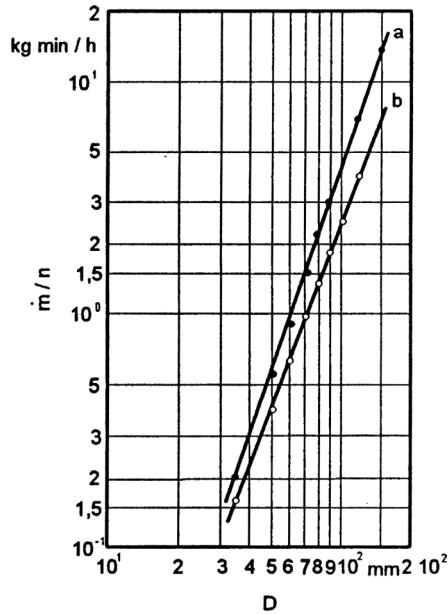


Figure 7.38 Empirical screw design data [11]

## ■ 7.3 Extrusion Dies

Extrusion dies can be designed by calculating shear rate, die pressure, and the residence time of the melt as functions of the flow path of melt in the die [6]. Of these quantities, the die pressure is the most important as the desired throughput cannot be attained if the die pressure does not match with the melt pressure. The interaction between screw and die is shown in Figs. 7.39 and 7.40.

Common shapes of flow channels occurring in extrusion dies are shown in Fig. 7.41. Detailed treatment of die design is presented in [1] and [17]. The following areas of application of extrusion dies serve as examples to illustrate the relationship between die geometry and processing parameters:

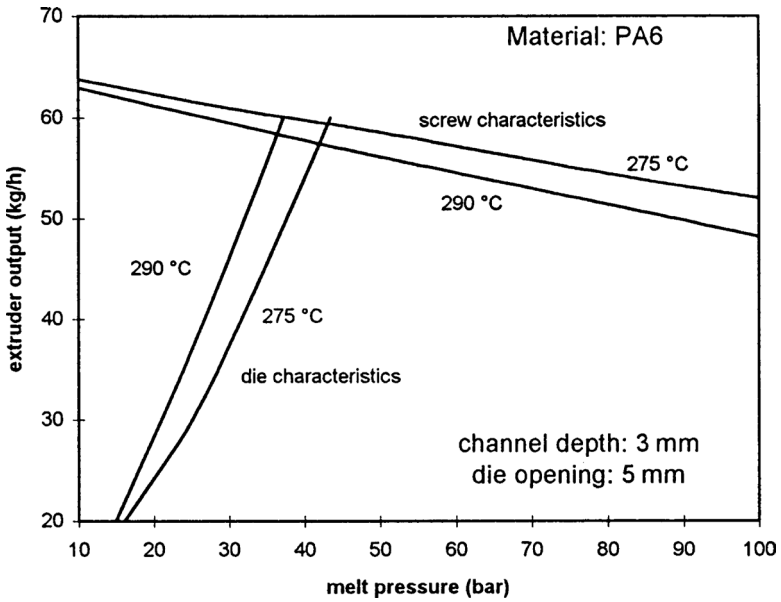


Figure 7.39 Effect of screw and die temperature

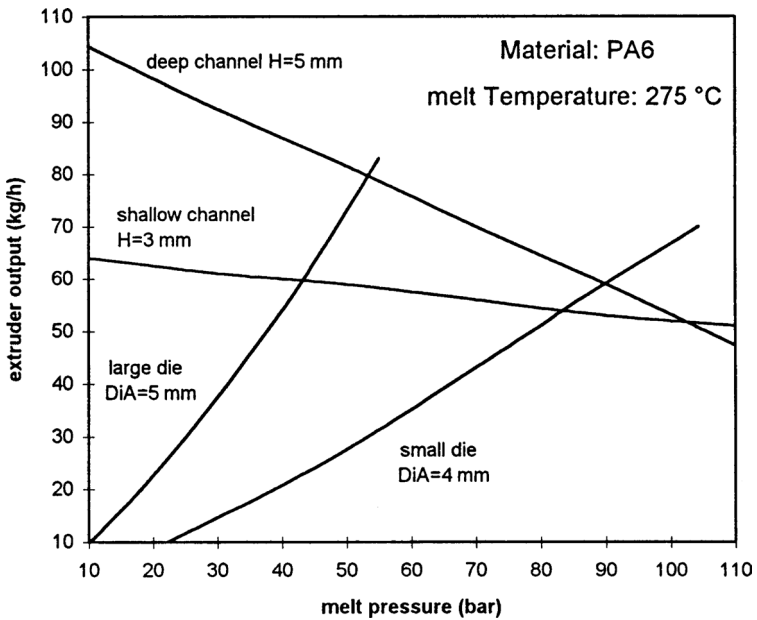
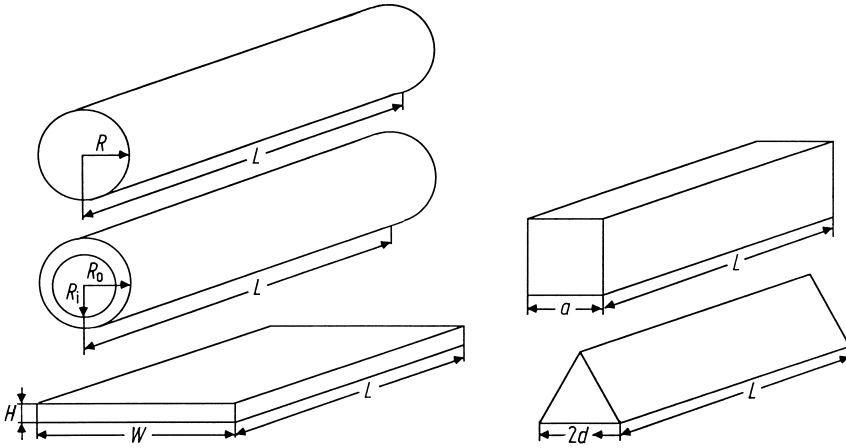


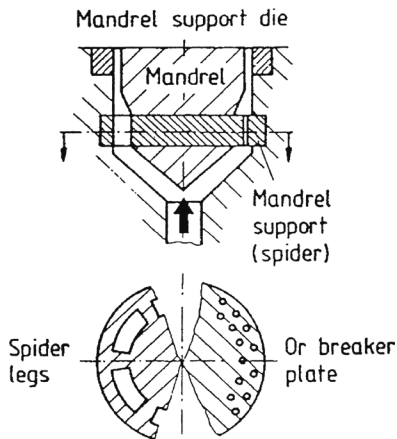
Figure 7.40 Effect of channel depth and die opening



**Figure 7.41** Common shapes of flow channels in extrusion dies [1]

### 7.3.1 Pipe Extrusion

The spider die shown in Fig. 7.42 is employed for making tubes and pipes and also for extruding a parison required to make a blow-molded article. It is also used in blown film processes.



**Figure 7.42** Mandrel support die with spider or breaker plate [17]

For a circular channel, the shear rate is given in Table 7.7. For an annulus, which represents the pipe cross-section, it is given by

$$\dot{\gamma}_{\text{annulus}} = \frac{6\dot{Q}}{\pi(R_o + R_i)(R_o - R_i)^2} \quad (7.28)$$

# Index

## A

absorption 100

## B

barrel screw 118  
Barr screw 112  
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