Design of Dies for the Extrusion of Sheets and Annular Parisons: The Distribution Problem

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A systematic design of the classical "coat hanger" die is proposed and tested experimentally. The objectives of the design are 1. distribution of the polymer over the width of the die before it reaches the final lip section for thickness adjustment, 2. invariance of distribution to flow rate, 3. invariance to changes in polymer viscosity, and 4. uniform average residence time. The die design is based on a flow model which assumes power-law viscosity, steady shear flow in each cross-section, uniform temperature, and separation of the flows into a manifold component and a component in a slit section of uniform height. The design corrects for an oversimplification of the pressure gradient that was applied in previous studies; and it differs from previous designs by suggesting a rectangular cross-section for the manifold. Applications to side-fed dies for extrusion blow molding and to a sheet extrusion die achieved uniform distribution and did not require any additional flow corrections (such as choker bars or flexible lips). With the new design, the lip region of the die can freely be used for thickness control, fine tuning, or further shaping of the extrudate.

INTRODUCTION

Extrusion die design has the objective to find the optimal geometry of a flow channel that shapes a continuous polymer stream into an extrudate of prescribed cross-section and microstructure. Several criteria can be defined for selecting optimal geometry (1). Of these, this study is solely concerned with the distribution problem, a special component of die design which is important for the extrusion of large aspect ratio (width/height $\gg 1$) extrudates: the flow rate per unit die width has to be uniform across the die exit. Examples of such extrudates are sheets, films, pipes, and annular parisons for blow molding. In the following, these dies will be called "large apect ratio extrusion dies" (LARED). The given geometrical data are the cross-section at the die inlet and the cross-section of the polymer extrudate (which is different than the cross-section of the die exit). The distribution of the polymer in the die occurs through pressure flow, with a high pressure at the die inlet and a negative pressure gradient in flow direction.

Several important aspects of die design are *not* covered here, such as swelling (2), development of macromolecular orientation (3), uniformity of strain history, non-uniform temperature and viscous dissipation (4), multilayer extrusion (5), melt fracture, manufacturing, and stiffness of the hardware.

LARED are conveniently composed of two geometrical regions, a wide manifold of low flow resistance, and a narrow slit region (gap thickness *h*) of high flow resistance. The polymer flows from the extruder into the manifold, and from there into the slit region. The most common designs of sheet extrusion dies are the "coat hanger" die as shown in *Fig. 1* and the "T-bar" die (6, 7). The name of the designs mimics the shape of the manifold. An alternative distribution system by Röthemeyer (8) found application only in extrusion of thick sheets. Cross-head dies, (9, 10) which are side-fed extrusion dies for extruding annular shapes, require the same design considerations with respect of the distribution problem as sheet extrusion dies.

The "coat hanger" die has been studied widely (5, 11–17). These derivations, however, are based on an over simplified momentum balance that results in a reduced flow rate at the outer edge of the distribution system. Additional flow resistors ("choke bars" or flexible die lips with adjustable resistance over the die width) were necessary to further the distribution of the polymer.

The objective of this study is to find a systematic design procedure for a distribution system that gives better uniformity of flow, i.e., uniform exit velocity and uniform average residence time over the die width. This uniformity should preferably be achieved with a die geometry that is independent of flow rate or polymer viscosity. The following derivation is valid for planar and for axisymmetric extrusion geometries. In the axisymmetric case, we neglect the influence of curvature.

FLOW MODEL OF LARED

The objective of the following model is to find the geometry of a distribution system of LARED. Given are the polymer flow properties (power law viscosity at uniform temperature), the width of distribution system, $2b$, and the volume flow rate

$$Q = 2bh\bar{v}_s. \tag{1}$$

During the following design procedure, the height of the slit, h, will be assumed to be given. h is prescribed by the flow rate of fluid and by a suitable choice of the wall shear rate in the slit region (see Eq 10). The maximum possible

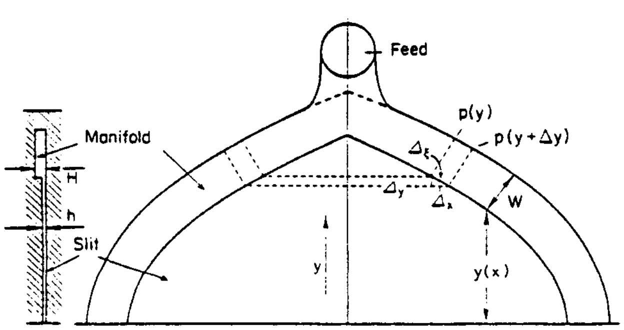


Fig. 1. Sketch of "coat hanger" distribution system with wide manifold and narrow slit flow region.

shear rate is given by the onset of elastic flow instabilities ("melt fracture"). Note that the slit height is not necessarily equal to the thickness of the extruded sheet or profile. The final thickness adjustment occurs (or should occur) in a separate die section, downstream of the distribution system.

The distribution system consists of a deep manifold of low flow resistance and a narrow slit region of high flow resistance, as shown in *Fig. 1*. The flow rate in the manifold decreases with increasing x. A simple mass balance prescribes that the rate of material passing through the manifold at position x, $Q_m(x)$, is equal to the rate of material which exits the system between x and b. At constant density, the local flow rate in the manifold is

$$Q_m(x) = A(x)\bar{v}_m = (b - x)h\bar{v}_s \tag{2}$$

where $\bar{v}_m$ and $\bar{v}_s$ are the average velocities in the manifold and in the slit. $A(x)$ is the cross-section of the manifold.

For the momentum balance, we assume that the discharge from the manifold into the slit region does not significantly influence the pressure gradient in the manifold. The pressure gradient normal to a cross section of the manifold is taken to be constant throughout the cross section. It is further assumed that the flow in the slit region occurs strictly in y-direction. Normal to the flow direction, lines of constant pressure can be drawn, as shown in *Fig. 1*. This relates the pressure gradient in the slit region with that in the manifold by

$$\left(\frac{dp}{dy}\right)_s = \left(\frac{dp}{d\xi}\right)_m \frac{\Delta\xi}{\Delta y} \tag{3}$$

with $\Delta\xi$ being the small length element in manifold direction which corresponds to the length element Δy in y-direction

$$\Delta\xi = \Delta y\sqrt{1 + (dy/dx)^{-2}}. \tag{4}$$

The derivative dy/dx is the slope of the contour line $y(x)$ in *Fig. 1*. In previous models of the distribution system (5, 11, 12, 15), this contribution of the slope has been neglected by approximating $\Delta\xi \approx \Delta x$; the resulting error is extremely large at the ends of the manifold, $x \rightarrow b$, where the slope is large. This model, however, includes the effects of the sloped manifold. This is the main reason why this distribution system has a much different geometry and why it seems to distribute the material much more uniformly than previously published designs. Combining the two above equations relates the pressure gradients to the slope of the contour line

$$dy/dx = -\left[\left(\frac{(dp/dy)_s}{(dp/d\xi)_m}\right)^2 - 1\right]^{-1/2} \tag{5}$$

Equations 2 and *5* are the basic design equations. Some general conclusions can be drawn already:

—The slope of the manifold, dy/dx, depends on the shape and cross-sectional area of the manifold.
—A short die (small y) requires a small slope dy/dx. This can be achieved through a pressure gradient in the manifold that is much smaller than the pressure gradient in the slit.
—The pressure gradient in the slit is not free to choose. It depends on the operating conditions, the depth of the slit region, and the onset of elastic flow instability.
—One more condition is free to choose for making the design complete. Possible choices are constant slope of manifold (dy/dx = const.), uniform shear rate at the walls of manifold and of slit region, or uniform average residence time in the distribution system.

Two different methods are obvious for continuation of the design procedure. In the first method, one chooses a slope, dy/dx, as a function of x. This specifies the pressure gradient in the manifold and the manifold cross section. This design has been investigated by Vergnes *et al.* (18, 19) who chose a manifold of constant slope. In the second method, one prescribes uniform wall shear rate at manifold and slit, eliminates the pressure gradient in Eq 5, and integrates to get the contour $y(x)$. In the following, we will use this second design method.

Power-law Viscosity

The pressure gradient and the shear rate at the wall of manifold and slit region are described with a very simplified flow model. The viscosity is given by a power law

$$\eta = \eta^{\circ}|\dot{\gamma}/\dot{\gamma}^{\circ}|^{n-1} \qquad (6)$$

with a reference viscosity, η°, at the reference shear rate, $\dot{\gamma}^{\circ}$, and a power law exponent, n. The flow is modeled by isothermal steady shear flow in a channel of constant cross section. For simple cross sectional geometries, the pressure gradient in flow direction and the shear rate at the wall are calculated as

circular: $$p' = -\frac{2\eta^{\circ}\dot{\gamma}^{\circ}}{R}(-\dot{\gamma}_w/\dot{\gamma}^{\circ})^n, \qquad (7)$$

$$\dot{\gamma}_w = -(1/n + 3)2\bar{v}/R, \qquad (8)$$

slit: $$p' = -\frac{2\eta^{\circ}\dot{\gamma}^{\circ}}{h}(-\dot{\gamma}_w/\dot{\gamma}^{\circ})^n, \qquad (9)$$

$$\dot{\gamma}_w = -(1/n + 2)2\bar{v}/h. \qquad (10)$$

The equations are derived by introducing the power law viscosity into the stress equation of motion. The average velocity, $\bar{v}$, is defined by the volume flow rate in the channel divided by the channel cross section.

For flow in a rectangular channel, one might define a representative shear rate at the wall, as given in *Eq 10*, and a pressure gradient

$$p' = -\frac{2\eta^{\circ}\dot{\gamma}^{\circ}}{h}(-\dot{\gamma}_w/(f_p\dot{\gamma}^{\circ}))^n, \qquad f_p \le 1. \qquad (11)$$

The shape factor, f_p, (see Ref 2, *Eq (10. 3-27)*) depends on the aspect ratio W/H of the rectangular cross section and on the power law exponent. From the following derivations, it will become clear that it is advantageous to choose an aspect ratio of $W/H > 10$. Then, the influence of the side faces of the channel is negligible and the shape factor has a value which is close to unity.

When applying these equations to the design of the distribution system, several more or less severe assumptions have to be introduced:
—lubrication approximation for the tapered manifold;
—the fluid discharge from the manifold into the slit region is assumed to have negligible influence on the flow in either region;
—the curvature of the manifold is assumed to have negligible influence; and
—no slip condition.

For the slight taper of the manifold, the lubrication approximation is very good (Ref. 6, p 224). The fluid discharge introduces a small side component to the flow in the manifold. This velocity component to the side is much smaller than the velocity in manifold direction. Entrance flow effects from the manifold into the slit will be minimized in this design by making the shear rates in manifold and slit region the same. The curvature of the manifold is small over most of the die width. However, it might have a significant influence at the outer edges of the distribution system.

The no-slip condition is satisfied for most polymers. For the case of a finite velocity at the wall, i.e., for slipping, the design has to be reconsidered from the beginning. Slipping will not be discussed in the following.

Specific Choices of Manifold Geometry

Many different cross-sectional shapes of the manifold are conceivable. The manifold with circular cross section or approximations thereof are found in most commercial extrusion dies, while the manifold with rectangular cross section has been introduced only recently (20, 21).

In the following, we will choose specific cross-sectional geometries for the manifold and calculate the corresponding contour lines $y(x)$. Each of the designs is based on *Eq 1* to *11* and the corresponding assumptions. The main criteria for the comparison of the different manifold geometries are
—invariance to viscosity change,
—invariance to flow rate, and
—uniform residence time over the width of the die.

These criteria are important in cases where the same die is used for extruding a variety of different polymers and at different extrusion rates. Uniform residence time is advantageous for extruding reacting polymers or for achieving short self cleaning time when changing the extrusion material.

CASE 1: CIRCULAR MANIFOLD

For modeling LARED, the most common choice of cross-sectional shape is the circle. Knappe and Schönewald (12) suggested to choose a uniform shear rate at the walls of manifold and slit. With this condition, they attempt to make the design invariant to viscosity changes. *Equations 8* and *10* for the shear rate at the wall of manifold and slit are set equal. The ratio of the average velocities is replaced by *Eq 2*, and we find the manifold radius

$$R(x) = h\left[\frac{(b-x)(1+3n)}{\pi h(1+2n)}\right]^{1/3}. \qquad (12)$$

The slope of the manifold is found by introducing *Eqs 7* and *9* into *Eq 5*. Integration gives a contour

$$y(x) = \frac{3Bb}{2}\left[\frac{\sqrt{1+g(x)}}{g(x)} - \frac{1}{2}\ln\frac{\sqrt{1+g(x)}-1}{\sqrt{1+g(x)}+1}\right] + C \qquad (13)$$

for $x/b \leq (1-B)$

with $g(x) = ((R/h)^2 - 1)^{-1}$; $\quad B = \frac{\pi h}{b}\frac{1+2n}{1+3n}$.

The choice of the integration constant, C, depends on the geometry of the manifold at the outer edge, $y = 0$. With $R = h$ at the outer edge, the integration constant becomes zero.

The manifold geometry is independent of the viscosity level, η^0. However, it depends on the magnitude of the power-law exponent, n. We have to search further to achieve invariance to material changes.

CASE 2: RECTANGULAR MANIFOLD

The most natural geometry for the manifold seems to be the slit cross section (20). With this choice, the flow in the manifold is similar to the flow in the slit region. Changes of viscosity or of flow rate affect the flow in the two regions in the same way. As a result, the die geometry is insensitive to material changes or to changes in processing conditions.

The ratio of the pressure gradients in manifold and slit region are independent of viscosity, if

$$\dot{\gamma}_s = \dot{\gamma}_m/f_p. \qquad (14)$$

This can be rearranged using *Eq 10* twice, once for the manifold and a second time for the slit region. Equating these two equations gives a relation between average velocities and manifold cross section. The average velocities are eliminated using *Eq 2*, and we obtain an expression for the manifold depth

$$H = h[(b-x)/(f_p(x)W(x))]^{1/2} \qquad (15)$$

With *Eqs 9* and *11*, the equation of the manifold slope becomes

$$dy/dx = -[(b-x)/(f_p(x)W(x)) - 1]^{-1/2}. \qquad (16)$$

For a manifold of *constant width*, W, the geometry is given by

$$H(x) = h\sqrt{(b-x)/(Wf_p(x))} \qquad (17)$$

and a contour which can be calculated analytically as

$$y(x) = 2W\sqrt{(b-x)/W - 1}; \quad f_p = 1. \qquad (18)$$

The dimensionless parameter of the solution

$$D = W/b$$

is given by the flowrate and the maximum shear rate at the wall which should be determined in a separate experiment with a slit flow rheometer.

For a manifold of *constant aspect ratio*, $W/H = a$, the manifold has the side faces

$$H(x) = h[(b-x)/(af_p h)]^{1/3} \qquad (19)$$

$$W(x) = aH(x) = [a^2h^2(b-x)/f_p]^{1/3}. \qquad (20)$$

The contour line is given by *Eq 13*, however with a function

$$g(x) = [(H(x)/h)^2 - 1]^{-1}. \qquad (21)$$

The integration constant is equal to zero, $C = 0$, given by the choice $H(x) = h$ at $y = 0$. The dimensionless parameter of the solution is defined as

$$B = ahf_p/b. \qquad (22)$$

For a wide manifold, $W \gg H$, the shape factor f_p is unity and the manifold becomes independent of the power-law exponent.

Uniform Average Residence Time

For some applications, it is advantageous to have uniform average residence time of material in the distribution system. Examples are reactive extrusion and rapid material change during extrusion. The residence time for an increment of manifold, $\Delta\xi$, has to be the same as the residence time for an equivalent increment of the slit, Δy:

$$\Delta t = \frac{\Delta y}{\bar{v}_s} = \frac{\Delta\xi}{\bar{v}_m}. \qquad (23)$$

The two displacements are related by *Eq 3*. Uniform average residence time is achieved with a contour slope.

$$\frac{dy}{dx} = -\frac{1}{\sqrt{(\bar{v}_m/\bar{v}_s)^2 - 1}}. \qquad (24)$$

Comparison of *Eqs 3* and *23* show that the velocity is related to the pressure gradient by

$$\frac{(dp/dy)_s}{(dp/d\xi)_m} = \frac{\bar{v}_m}{\bar{v}_s}. \qquad (25)$$

This condition is already satisfied for the rectangular manifold with $f_p = 1$ and uniform wall shear rate. For the circular manifold, in comparison, it is not possible to achieve uniform residence time *and* uniform wall shear rate.

Summary of the Model

In summary, the model gives three different design equations for the geometry of the manifold

a) *Eqs 12* and *13* for the circular cross section,
b) *Eqs 17* and *18* for the rectangular cross section of constant width W, and
c) *Eqs 13, 21*, and *22* for the rectangular cross section of constant aspect ratio $a = W/H$.

The design equations for the circular manifold depend strongly on the power law exponent. This is a major disadvantage of the conventional design since each polymer requires a different die geometry. This inherent problem is resolved with a manifold of rectangular cross-section. The design equations for the rectangular manifold are independent of the power law parameters if the shape factor, f_p, is approaching unity. This is the case for cross-sections with a large aspect ratio, $W/H > 10$.

INFLUENCE OF DESIGN PARAMETERS

The die geometry is largely dependent on the choice of design parameters such as the aspect ratio of the manifold and the depth of the slit region. These design parameters have been varied over a wide range with the objective to achieve short extrusion dies, (small $y(0)$), as required for very wide dies (large b). For small sheet extrusion dies, blow molding dies, or wire coating dies it is not as important to find a die geometry of short length $y(0)$. *Figure 2* shows the contour line $y(x)$ for a distribution system with a manifold of constant width W. Parameter of the curves is the width of the manifold normalized with the width of the entire distribution system. The shortest die was achieved with the most narrow manifold. A lower limit is, of course, given by $W/H > 10$, which is required to maintain slit flow in the manifold. Otherwise the pressure drop in the manifold has to be calculated using a shape factor f_p below unity.

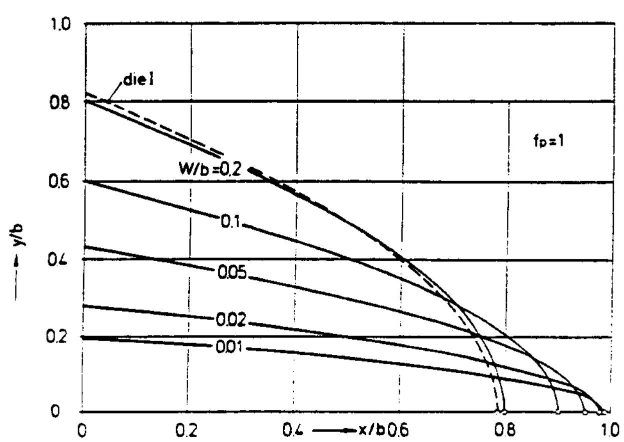


Fig. 2. Calculated contours for manifolds with rectangular cross section of constant width W. The dashed line shows the geometry of the first die of the blow molding applications as discussed below (see Fig. 12).

The influence of the shape factor will be discussed below.

The length of the die depends on a combination of several geometrical parameters as shown in *Fig. 3*. For a given width of the distribution system, b, the shortest die is found with a small depth of the slit region, h, and a small aspect ratio W/H. This is true for the manifold of constant width and for the manifold of the constant aspect ratio W/H as compared in the figure. The die length was found to depend on a single geometrical parameter, D or B, which is dimensionless. This parameter will be used in the next two figures to describe possible geometries of dies with a manifold of constant aspect ratio W/H = const. *Figure 4* shows contour lines as calculated with *Eqs 13, 21* and *22*. The corresponding depth of the manifold is given in *Fig. 5*. For manufacturing purposes it is interesting to note that the manifold depth is nearly constant in the center region of the distribution system, and it decreases rapidly near the end of the manifold.

In the first design examples, the influence of

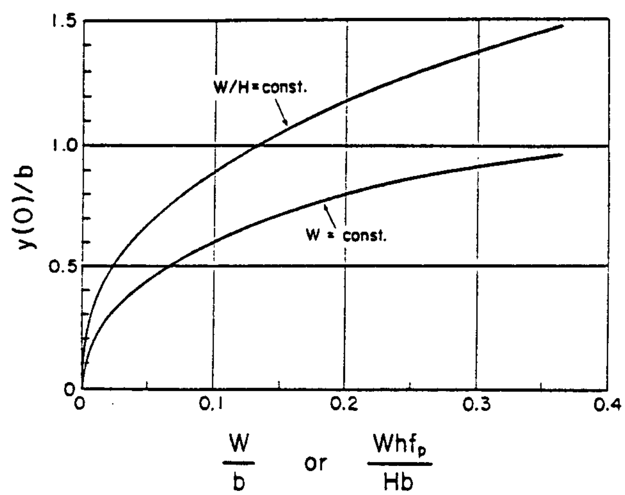


Fig. 3. Length of the slit region for distribution systems with manifolds of rectangular cross sections.

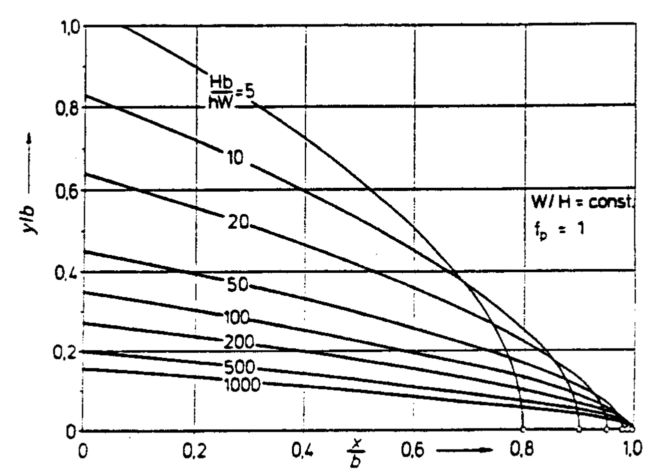


Fig. 4. Contour of manifolds with rectangular cross section of constant aspect ratio W/H. The influence of geometry is given by a single dimensionless parameter.

the side walls of the manifold has been neglected by taking a shape factor $f_p = 1$. This is an oversimplification which leads to significant errors in cases of manifolds with small aspect ratio W/H. The solid lines in *Fig. 6* give the length of the die as calculated using a shape factor f_p as given by Tadmor and Gogos (2). In comparison, the dashed line gives the die length as calculated without using the shape factor ($f_p = 1$). Obviously, the error becomes large when the aspect ratio approaches unity. The value of the shape factor depends on the power law exponent of the viscosity. However, influence of the power law exponent is much smaller than the influence of the correction factor f_p, as shown in *Fig. 7*.

FIRST APPLICATION: DISTRIBUTION SYSTEM FOR PROFILE DIE

A LARED profile extrusion die ($2b = 200$ mm) has been equipped with a distribution system according to *Eq 17* and *18*. A schematic of the die is given in *Fig. 8*. In this design, the distribution of polymer and the final shaping operation is separated into a sequence of two independent steps. The distribution of polymer was found to be practically uniform over the die width. As seen in *Fig. 9*, no additional distribution aid was required. The polymer stream directly enters the shaping region of the profile die. The test material was a commercial PP (Vestolen P 2421, Hüls). An extrusion pressure of 65 bar at a temperature of 230°C gave an average extrusion speed of 41 mm/s.

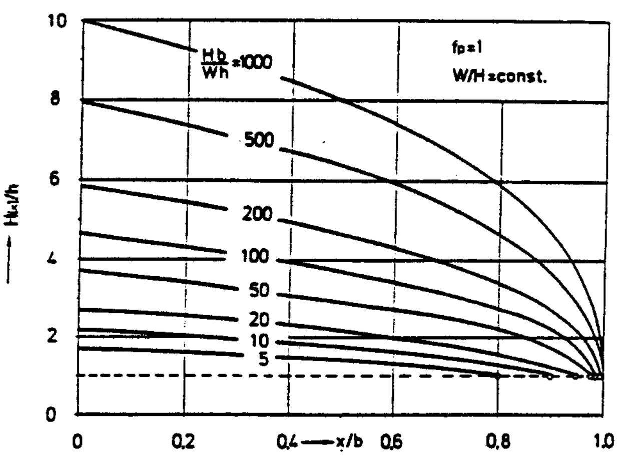


Fig. 5. Depth of manifolds with rectangular cross section of constant aspect ratio W/H.

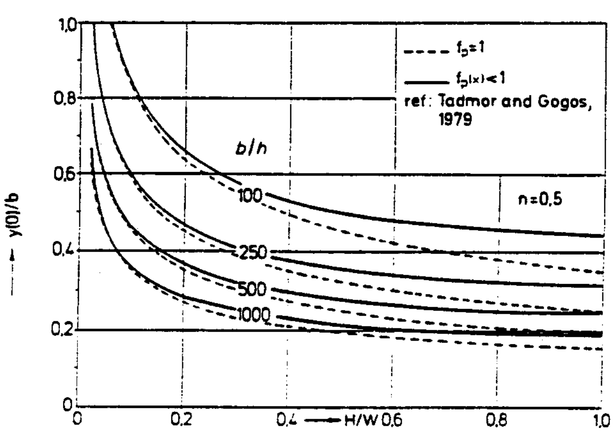


Fig. 6. Calculated die length as a function of geometrical parameters. The solid line accounts for the influence of the sidefaces (use of shape factor). The dashed line is the calculated die length neglecting the influence of the sidefaces of the manifold.

SECOND APPLICATION: BLOW MOLDING DIES

Apparatus and Materials

The model has been applied to the design of a distribution system for the blow molding die of *Fig. 10*. Three different cores with a diameter $2R = 60$ mm are shown in *Fig. 11*. The detailed geometry of the distribution system is given in *Fig. 12*. The distribution system was cut into the inner cylinder (core), while the outer cylinder remained unchanged for the three different dies. Special features of the three dies are the following:

—Die I has a constant manifold width $W = 20$ mm, while the depth decreases from 3.9 mm to the final depth of 1.8 mm in a continuous fashion.

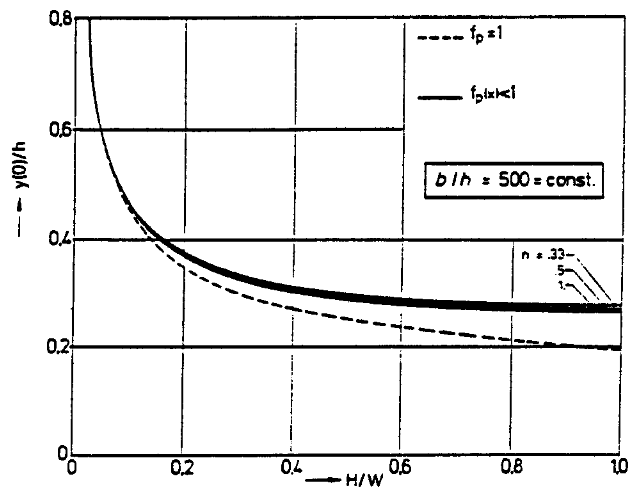


Fig. 7. Influence of the power law exponent on the calculated die length. The manifold width is held constant.

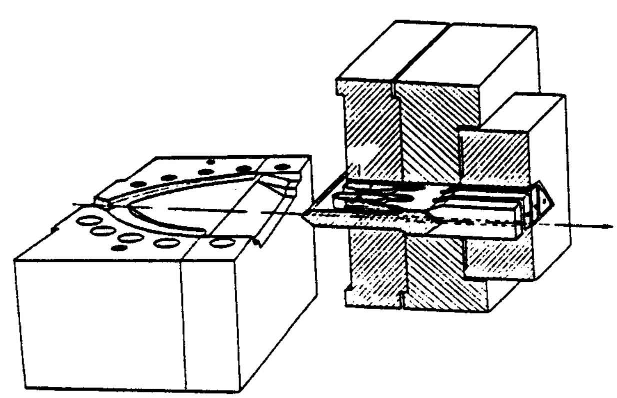


Fig. 8. Sketch of large aspect ratio profile extrusion die which is fed by a separate distribution system.

—The second die, die II, was designed with a manifold of constant aspect ratio, $W/H = 1.5$. With this low value, it is necessary to use a shape factor to correct for the flow resistance of the side walls of the manifold. Die II is shorter and, therefore, has a significantly lower pressure drop and lower length of the slit region compared to die I.

—The design of die III has the objective to overcome the problem of the weld interface between the two streams as they are combined at the end of the manifold. In this design, an overlap region was introduced by increasing the width of the distribution system, $2b$, to a larger value, $2b + W$. Near the weld interface a third stream is generated through a small channel from one of the manifolds. The three streams are recombined to minimize the influence of the weld.

Fig. 9. Distribution system with manifold of constant width as used for profile extrusion.

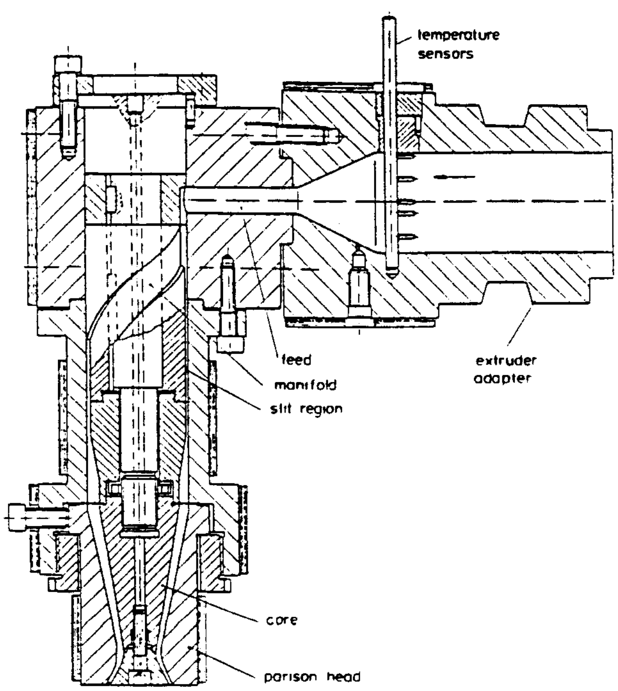


Fig. 10. Cross section of extrusion blow molding die as used in experimental study of distribution model.

Extrusion experiments have been performed with five commercial polymers, four HDPE and one PP. Measured viscosity curves are given in *Fig. 13*. The power law exponent for the viscosity varied between [n = 0.2 and 0.4.] The onset of flow instability is marked by the critical shear rate, $\dot{\gamma}_c$.

Experimental Results with Blow Molding Dies

Annular parisons have been extruded from all three dies under variation of polymer, extrusion rate, and die resistance downstream of the distribution system. In the first experiments, the parisons were extruded into a cold silicon oil bath (25°C). After solidification, the circumferential distribution of wall thickness and the swell was measured. The distribution of wall thickness was determined with a mechanical thickness gage. In a second series, bottles were blown from the parisons and again the circumferential wall thickness distribution was measured by infrared absorption (Gawis 1000, Sohlberg Ab, Finnland). Experimental observations with the three dies are the following:

—Parisons from die I and die III had a very

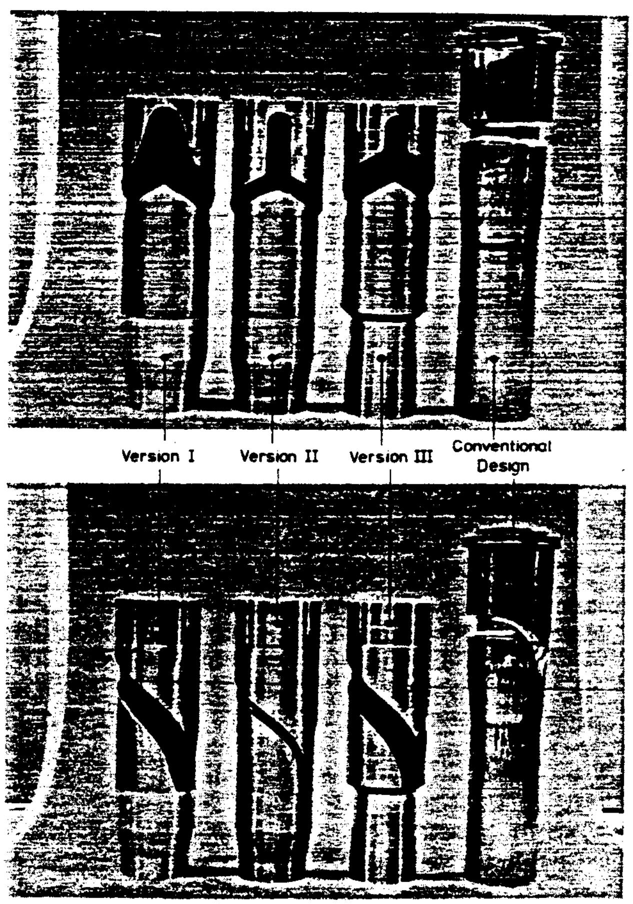


Fig. 11. Four different cores or extrusion blow molding dies (see Fig. 10) are shown in front view (top) and in side view (bottom). The three dies on the left were designed with the flow model of this study. The core on the right side was used in a commercial blow molding die and is shown for comparison.

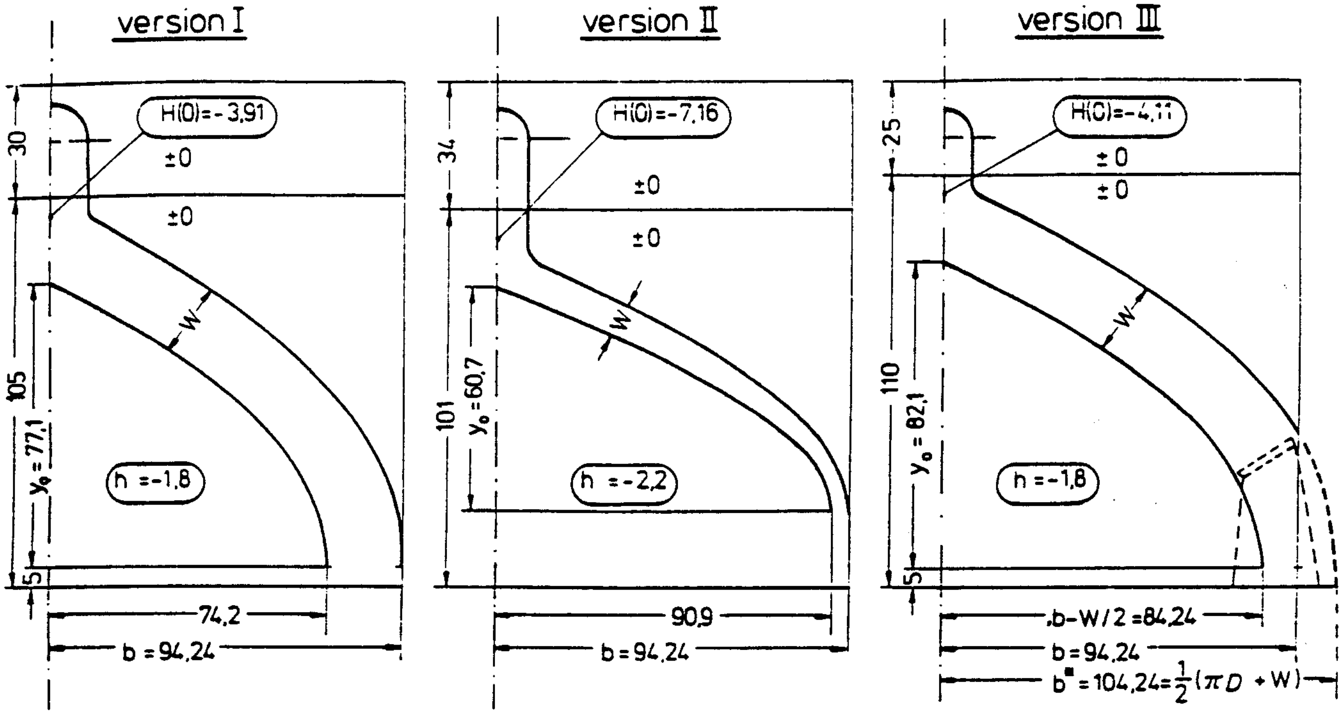


Fig. 12. Manifold and slit geometry of dies I. II. and III.

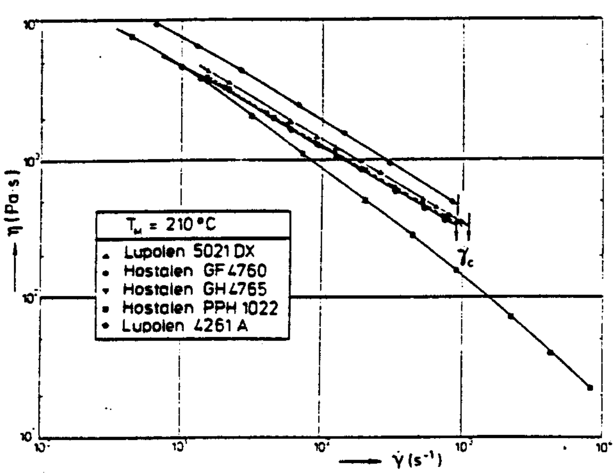


Fig. 13. Steady shear viscosity of five commercial polymers as used in blow molding experiments. The critical shear rate indicates the onset of flow instability during the viscosity measurement.

narrow thickness distribution ($\Delta s/s$ = 3.5 percent). The variations were much smaller than for die II ($\Delta s/s = 7$ percent), see *Fig. 14*. It can be concluded that manifolds with a larger aspect ratio W/H give a better distribution than manifolds with small aspect ratio, even if a correction factor f_p is used in the calculation of the manifold geometry.

—Die III gave an equally good distribution as die I, however, with the advantage of improving the welding region at the end of the manifold.

—The magnitude of the flow rate had no significant influence on the variation of wall thickness. This is shown in *Fig. 15*.

—The distribution was more uniform for PP than for the four HDPE as shown in *Fig. 16*. This difference is attributed to differences in the elastic properties of the molten polymers that are not included in the flow model of the distribution system.

—Modifications of the flow resistance downstream of the distribution system had little influence on the wall thickness distribution. Variations in resistance were achieved by changing the exit region of the annular die, using annular gaps between 1.2 and 2.2 mm. Thickness distributions on blown bottles were found to be between 10 and 12 percent for a wall thickness of about 1 mm on the blown bottle. Circumferential thickness gradients were found to be very small, giving no problems for succeeding surface treatment for printing.

—Differences in residence time distribution were measured by color changes in the feed. For die I, the residence time down the slit region as compared to the residence time for flow along the manifolds differed by a factor of about two. The longest residence time was found for the material in the weld interface.

CONCLUSIONS

The design procedure gives the geometry of distribution systems for large aspect ratio extrusion dies. For the manifold, slit cross sections are preferred to circular cross sections, since they give a die geometry that is practically independent of polymer viscosity and/or flow rates. A universal design concept applies to planar sheet extrusion dies and to side-fed annular dies. Based on the conservation of mass

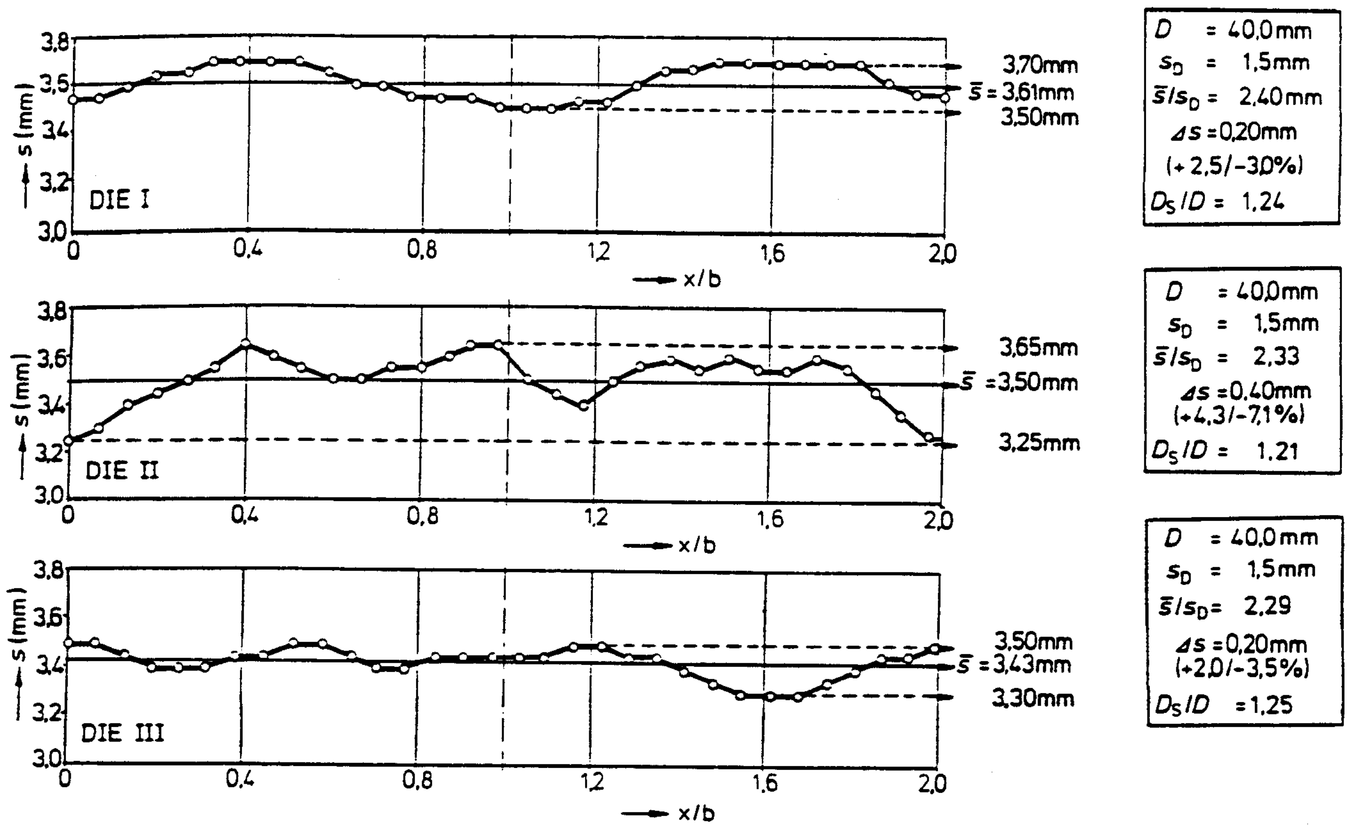
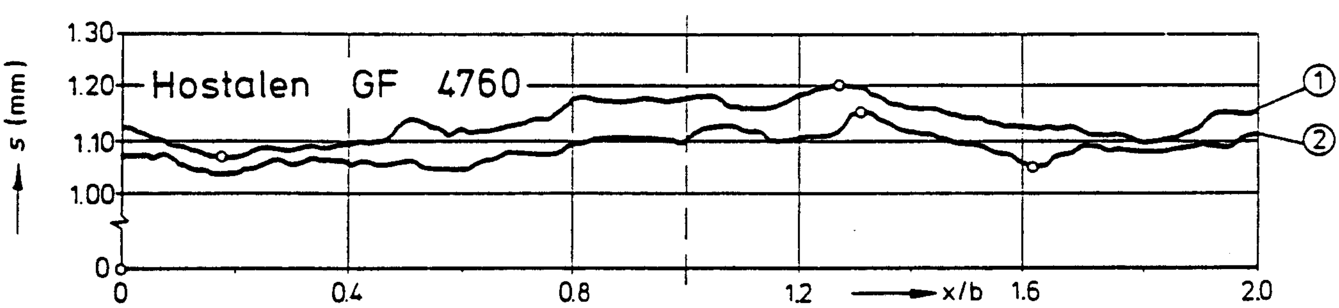


Fig. 14. Measured wall thickness distributions of parisons from dies I, II, and III: Hostalen GF 4760; Q = 25 kg/h.



run 1: Q = 28.0 kg/h; s_{min} = 1.06 mm; $\bar{T}_M$ = 226 °C; s_{max} = 1.19 mm; $\bar{s}$ = 1.13 mm;

run 2: Q = 22.9 kg/h; s_{min} = 1.03 mm; $\bar{T}_M$ = 224 °C; s_{max} = 1.15 mm; $\bar{s}$ = 1.08 mm;

Fig. 15. Measured wall thickness distributions of parisons which are extruded at different rates: continuous IR measurement; die I.

and momentum, the stepwise design procedure allows for accommodation of phenomena such as critical pressure drop in the die, separation force between the die halfs, and onset of melt fracture.

The primary function of the distribution system is to achieve uniform velocity across the exit of the die and to achieve uniform wall thickness of the final extrudate. This has been experimentally verified with a large aspect ratio profile die and with blow molding dies which were side-fed by an extruder. In both cases, the distribution was found to be practically uniform over the width of the die.

An important parameter of the die design is the length of the slit region, $y(0)$. Large sheet extrusion dies, $b > 600$ mm, require a short slit region. Otherwise the pressure drop across the die is too large, the steel walls of the die may deform significantly, and the prescribed geometry would not be maintained during the operation. Low values of pressure and separation forces can be achieved by choosing a small depth of the slit region, h, and a small aspect

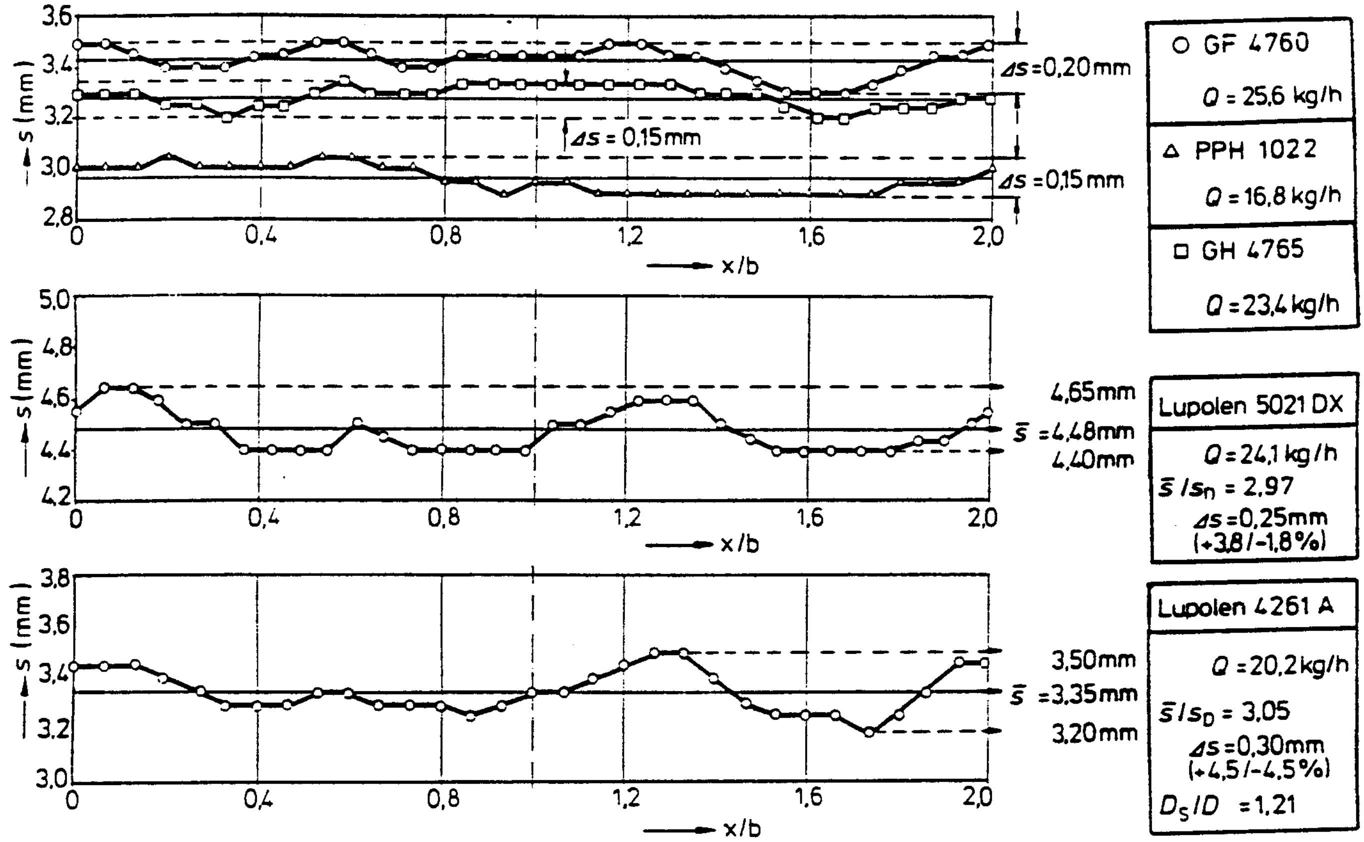


Fig. 16. Comparison of the measured wall thickness distributions for parisons of three polymers, using equivalent extrusion conditions: die III.

ratio W/H. However, a small aspect ratio W/H requires the use of a shape factor, $f_p < 1$, in the design procedure. Small values of the slit depth, h, are achieved by operating the die at the maximum possible shear rate below the onset of melt fracture.

Immediate applications of this design concept are seen in the areas of extrusion blow molding, sheet extrusion, extrusion of large aspect ratio profiles, and wire coating.

ACKNOWLEDGMENT

The computer input for the numerically controlled manufacturing has been prepared by Dipl.-Ing. U. Pfau. One of the authors (H. H. Winter) gratefully acknowledges the support from General Electric, Plastics Division.

NOMENCLATURE

a = aspect ratio of rectangular manifold, W/H
b = half width of sheet die or half circumference of annular die
f_p = shape factor for flow rate in channel with rectangular cross section
h = depth of slit flow region
H = depth of rectangular manifold
n = power law exponent
p = pressure
Q = volume flow rate
R = radius of annular die (at distribution region).
s = thickness of extrudate
$\bar{v}_m$ = average velocity in manifold
$\bar{v}_s$ = average velocity in slit region
W = width of rectangular manifold
x, y = coordinates
$\dot{\gamma}$ = shear rate
η = shear viscosity
ξ = coordinate in direction of manifold

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