Residence-Time Distribution Model for Twin-Screw Extruders

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A model for the residence-time distribution (RTD) is validated by the analysis of data collected from the extrusion of polyethylene on a 30-mm Krupp Werner and Pfleiderer (W&P) corotating twin-screw extruder. Transformation of the RTD to give both the residence-volume distribution (RVD) and the residence-revolution distribution (RRD) yields new physical insights into the extrusion process. It is observed that operating conditions with equivalent specific throughput result in an equivalent RVD and RRD, and for a given screw configuration the axial mixing of extrusion material as measured by a tracer is essentially the same for all operating conditions. This allows the experimental RVD curves to be superimposed to form a single master curve for a given screw geometry. These new tools motivate the development of a simple residence model that characterizes the partially filled and fully filled screw sections and is capable of distinguishing between screw configurations and operating conditions. A least-square error-fit method used to identify the parameters of the RTD model indicated that the model function is appropriate to describe the RTD experimental data.

Introduction

The elements of fluid taking different routes through a twin-screw extruder may require different lengths of time to pass through the extruder. The distribution of these times for the stream of fluid leaving the extruder is called the residence-time distribution (RTD) (Levenspiel, 1972), which has been used extensively in the literature to characterize the polymer extrusion processes (Weiss and Stamato, 1989; Cassagnau et al., 1991; Kim and White, 1994; Chen et al., 1995b; Wetzel et al., 1997). The RTD curve is generally measured by adding a tracer material into the extruder and detecting the concentration of the tracer using a probe mounted at a position further down the flow path of the extruder. When represented in normalized form the RTD function is defined by Eq. 1:

$$e(t) = \frac{c(t)}{\int_0^\infty |c(t)|\,dt}, \tag{1}$$

where $e(t)$ is the RTD function and $c(t)$ is the filtered probe response. Time zero is understood to be the time when the tracer material is added into the extruder.

For reactive extrusion processes where the reaction time is the same order of mean residence time—for example, some types of peroxide initiated degradation to polypropylene—the RTD is of interest, since the length of time that the material remains in the extruder should be closely coupled to

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the reaction kinetics and hence greatly impact product quality. For mixing applications that do not involve a time-dependent process, the RTD may be less important. In many cases the most natural coordinate in which to study material behavior in an extruder is not necessarily time, but either the number of screw revolutions or the extrudate volume. Each of these can be obtained from the independent variable time by a simple transformation resulting in two new distribution functions: the residence-revolution distribution (RRD) function $f(n)$, and the residence-volume distribution (RVD) function $g(v)$. These two functions are defined in Eq. 2:

$$f(n) = \frac{c\left(\frac{n}{N}\right)}{\int_0^\infty \left| c\left(\frac{n}{N}\right) \right| dn} \qquad g(v) = \frac{c\left(\frac{v}{Q}\right)}{\int_0^\infty \left| c\left(\frac{v}{Q}\right) \right| dv}, \quad (2)$$

where Q is the material throughput (L/min) and N is the screw speed (r/min). The integration variables in $h(n)$ and $g(v)$ are the screw revolutions (n) and extrudate volume (v), respectively, after the tracer is added into the extruder. Their relationship with time t is $t = n/N = v/Q$. The RVD is a direct measure of the physical distribution of tracer in the extrudate along the extrusion (axial) direction, assuming an impulse input. Given a sample of extrudate, the RVD curve is the profile of the tracer concentration along the axis of the sample, which can be taken as a measure of the effectiveness of the axial mixing process for the specific extrusion conditions. It is useful to separate extrusion into two types of physical processes: transport and mixing. The RRD gives insight into the transport behavior of the extruder, while the RVD gives insight into the mixing process, albeit in only a limited manner. The insight into the mixing process obtained from the RVD is limited because the axial distribution of the material is only one aspect of mixing behavior, and many other factors such as the size scale of the phases, the concentration gradient of the components, and the uniformity of the distribution cannot be directly determined from the RVD. In this article we show that the specific throughput, defined as Q/N (liter per screw revolution), is the key factor is determining the characteristics of the RRD and RVD for the twin-screw extruder used in this work. The RRD and RVD are examined under a variety of operating conditions for two screw geometries, and a simple model characterizing the fully and partially filled screw sections is developed for the RTD. The basic features of the RRD and RVD can then be explained by simple modifications of this model.

In order to obtain a comprehensive picture of the work done by previous researchers to characterize the extrusion process, some RTD models are reviewed. Naor and Shinnar (1963) supplied an RTD model for several identical exponential vessels connected in series. The plug flow was treated as an extreme case in which the number of vessels tended to infinity. This model allows physical insight into the mixing process and helps to illustrate the basic features of the system. In later work by Janssen et al. (1979), a counterrotating, fully intermeshing twin-screw extruder with a double-thread start screw was modeled as a series of ideally mixed chambers connected in parallel with four types of leakage flows. A series of differential equations were formulated for the fully filled zone of the extruder, from which the distribution of residence times could be computed. In a recent work by Thompson et al. (1995), four empirical flow models—plug-flow-and-tanks-in-series (with and without recirculation); plug-flow-and-axial-distribution; and the Wolf-Resnick models—were tested by fitting the measured response data with models of a nonintermeshing twin-screw extruder. The plug-flow-and-axial-distribution model was found to provide the closest approximation to the measured distribution.

Some previous models are based on the analysis of the flow mechanism in an extruder. By approximating the flow channel as rectangular conduit and assuming that the channel depth is constant, Pinto and Tadmor (1970) derived the RTD functions for Newtonian flow in single-screw extruders, which was based on the ''parallel plate'' and curved-channel flow model. An analytical expression for the residence time was supplied and the minimum residence time was found to be equal to three-quarters of the mean residence time. This model was later extended by Bigg and Middleman (1974) to the case of a non-Newtonian fluid, and by Wolf and White (1976) to the case of a tapered channel.

Some researchers developed models that are based on statistical techniques in contrast to the ones described in the previous paragraph, which were based on physical modeling. Chen et al. (1993), developed a theory that involves the superposition of RTD functions of different screw sections with two-dimensional perfect mixing at the boundaries. Based on this theory, Chen et al. developed a predictive RTD model for an intermeshing counterrotating twin-screw extruder, which treats the screw as a set of individual turns connected in series, with the RTD from each turn assumed to be statistically independent of each other. The overall RTD function can then be expressed in the Laplace domain as the multiplication of the individual RTDs. This theory was also used by Chen et al. (1995a) in developing a predictive model for a nonintermeshing counterrotating twin-screw extruder based both on the flow analysis of individual screw zones and the statistical RTD superposition principle.

Although many models have been developed in the literature, most of them are inadequate for quantitatively predicting the RTD from a given set of operating conditions and the screw configuration. In this article, a simple, physically based model for the RTD will be presented, with which the features of the RTD, RVD, and RRD can be explained. The quality of the experimentally obtained RTD curves presented in this article also deserves mentioning. High-quality RTD data are necessary for developing a reliable model and to provide experimental validation. Due to the high sampling frequency and noise filtering (Gao et al., 1999), the RTD plots presented are of high quality relative to previously published work, and clearly reveal the process features predicted by the model.

In the following sections, the experimental setup will first be described, followed by investigation of the characteristics of the RVD and RRD. Examining the physical meaning of the RVD and RRD motivates the development of an RTD model, which reveals the effect of the partially filled and fully filled screw sections on the RTD. Slight modifications of the RTD model are then made to obtain the RVD and RRD

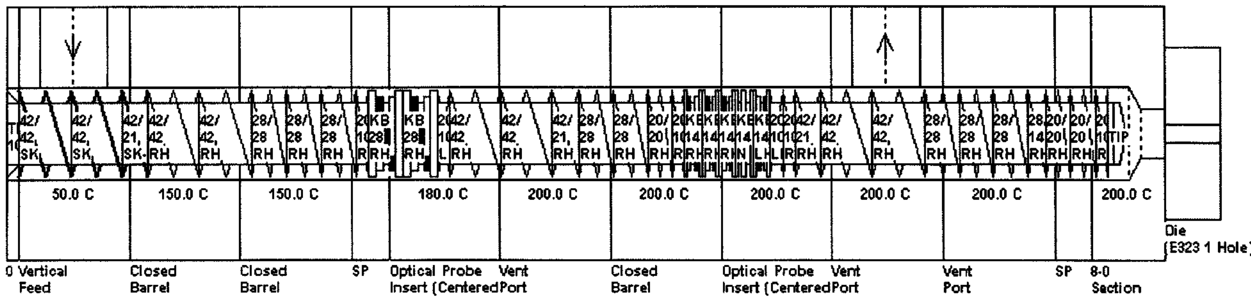

Figure 1. Screw configuration 1.

with which the features of these new distributions can be explained. The model is validated by comparing the experimentally obtained RTDs and the model-predicted RTDs.

Experiment

The experiments were carried out on a 30-mm W&P CoTSE extruder using the two-screw configurations shown in Figures 1 and 2. Both screw designs contain the same melting region (two right-handed 28-mm-long kneading blocks followed by a 10-mm-long 20-mm pitch left-handed conveying element). Screw configuration 1 contains a mixing region with three right-handed, one neutral, and one left-handed kneading blocks all 14 mm long, followed by a 10-mm-long 20-mm pitch left-handed conveying element. Screw configuration 2 has a less intense mixing zone compared to screw configuration 1, where the neutral and left-handed kneading blocks have been replaced by a 28-mm-long 28-mm pitch right-handed conveying element in front of the mixing zone. Two materials—high-density polyethylene (HDPE) Alathon M6060 and HDPE Alathon H6018—were used as extrusion material for each screw configuration to investigate the effect of extrusion material viscosity on the observed RTD. The two materials covered the range of viscosities of interest to our project, from a melt index (MI) of 6 (M6060) to a MI of 18 (H6018). No significant differences in the residence time distributions were observed between the two materials. The sensitivity of the RTD to viscosity we expected to find was not supported by our experimental data, and hence will not appear in our models.

Three reflective optical probes were mounted in the barrel of the extruder at the center of the melting zone, mixing zone, and at the die, respectively. The probe contains a bifurcated optical-fiber bundle enclosed in a stainless-steel shell that is inserted into another, larger stainless-steel shell with a sapphire window. The unit screws into the extruder barrel in standard Dynisco (Dynisco Inc., Sharon, MA) pressure transducer ports. The probe uses a split fiber-optic bundle, where white light is transferred through one fiber bundle, goes through the transparent windows, and enters the extrusion melt. The light is then scattered by the presence of a titanium dioxide tracer or reflected by the screw surface. The reflected and backscattered light enters the other fiber bundle and is converted to a voltage signal using a photodiode. The voltage is amplified and filtered and sampled by a PC-based data-acquisition system with a sampling rate of 60 Hz. The data stream is then downsampled and 20 samples per second are stored in a file on a PC.

The tracer material used to measure the RTD in the experiments is titanium dioxide (TiO_2), which is precompounded with the matrix material at a concentration of 20% by weight and made into pellets. Five tracer pellets were dropped into the feed throat after the data-acquisition system was sampling for 60 s. The addition of the tracer in the form of HDPE pellets is considered to be an impulse input of tracer material. Since the raw material does not contain any TiO_2, and only five tracer pellets are added for each experiment, the concentration of TiO_2 in the extrusion material is small enough so that its effect on viscosity change is negligible. Some articles (Weiss and Stamato, 1989; Cassagnau et al., 1991) indicate that the type of tracer can significantly affect the measurement of RTD. The TiO_2-based tracer yielded the best result when compared to other tracer materials with which we experimented, such as liquid dyes. Liquid tracers can result in lubrication and yield a significantly different RTD than a particulate tracer such as TiO_2. Twelve operat-

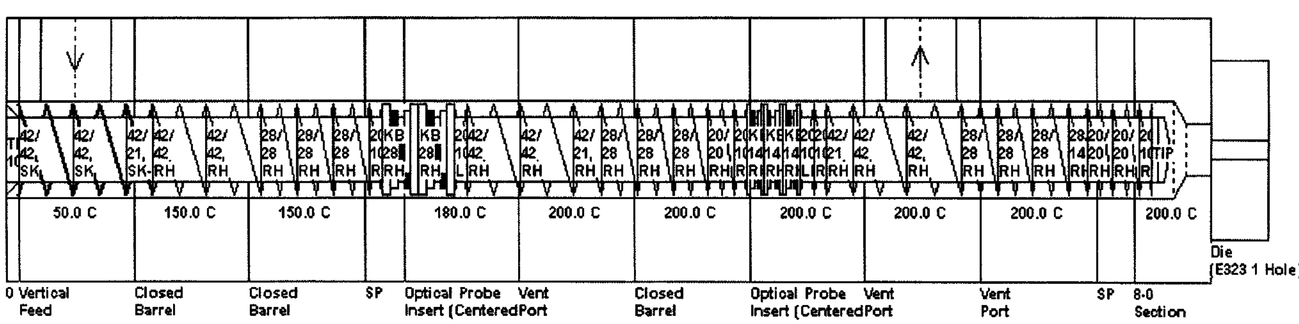

Figure 2. Screw configuration 2.

Table 1. Operating Conditions

Operating Condition	1	2	3	4	5	6	7	8	9	10	11	12
Volume Throughput ($\times 10^{-3}$ L/min)	178	178	178	178	356	356	356	88.9	88.9	267	267	267
Mass throughput (lb/h)	20	20	20	20	40	40	40	10	10	30	30	30
Screw speed (rev./min)	140	210	265	350	170	210	280	105	210	160	210	320
Specific throughput Q/N ($\times 10^{-3}$ L/rev.)	1.27	0.85	0.67	0.51	2.09	1.70	1.27	0.85	0.42	1.67	1.27	0.83

ing conditions shown in Table 1 were tested, with three replicates for each condition. After changing operating conditions, data were not collected for 5 min to allow steady-state operation to be achieved.

Probe response

The response from probes located at the mixing zone and at the die for operating condition number 2 are shown in Figure 3. The data have had the base line removed. The noise in the probe response is due to a periodic background signal created by reflection off of the rotating screw surface. The noise is reduced with a Butterworth digital filter (Stanley et al., 1984), and the smooth lines in Figure 3 are the filtered probe responses, which show initial and final dips in the die probe response. The dip is not an artifact of the filter used; notice that the RTD data of the mixing zone do not show any dip. The reason for the dip is that a large background signal exists at the die due to the strong reflection of the screw. Small concentrations of tracer actually decrease the light reflected back to the probe. As more tracer material reaches the probe, the increased scattering will give rise to the increased probe response. Figure 4 shows three characteristic parameters of the RTD curve: t_d, t_w, and t_m. The delay time, t_d, is the time interval between when the tracer is added and when the tracer is first detected by the probe. The mean residence time is defined with Eq. 3:

$$t_m = \int_0^\infty |e(t)| t \, dt. \tag{3}$$

The mean pulse time is defined as the mean residence time minus the delay time ($t_w = t_m - t_d$). For the simple model introduced later (Eq. 4), t_w is a measure of the width of the tracer pulse.

Data-processing issues

The steady-state base-line signal of the raw data is removed by subtracting the average value of the first 60 s of the data. A Butterworth filter is then used to reduce the high-frequency noise. The three filtered replicate data sets are time averaged to reduce the effect of process variability and the resultant data are used for normalization. The absolute value of the initial dip and tail of the filtered data are included in normalization. The data are normalized using Eq. 1.

Experimental Results

The RTDs at the die for the twelve operating conditions using HDPE Alathon M6060 as extrusion material are shown in Figure 5. It can be seen that for a given screw speed, a larger throughput will result in a sharper RTD and smaller time delay, and a greater screw speed will move the RTDs toward the left. The shapes of the RTDs at the die under the same throughput are all very similar to each other, while at the mixing zone, the shape of the RTDs generally becomes

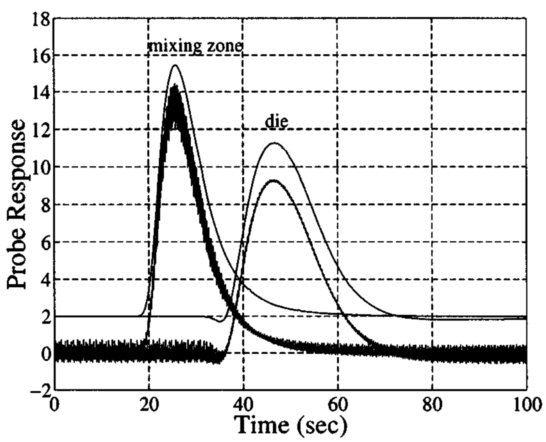

Figure 3. Raw and filtered data from the probes located at the mixing zone and at the die for operating condition 2: 0.178 L/min, 210 r/min.

A vertical offset is added to the filtered data to make the filtered data visible.

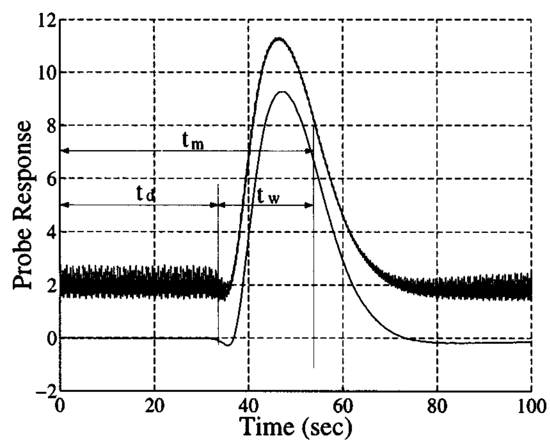

Figure 4. Raw and filtered RTD data.

A vertical offset is added to the raw data to make the filtered data visible.

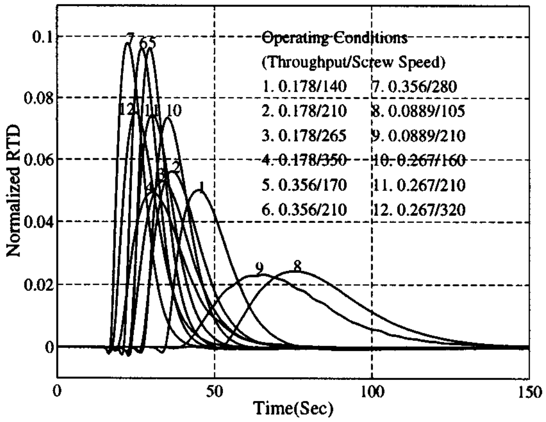

Figure 5. Experimental RTD data at the die for screw configuration 2 (Material:HDPE6060).

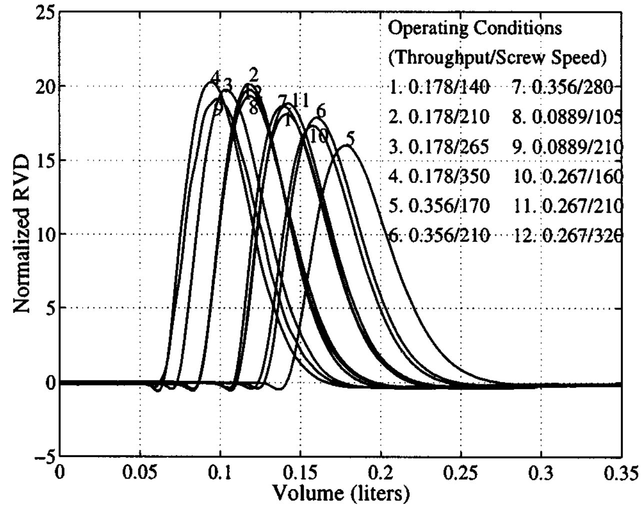

Figure 7. RVD at the die for screw configuration 1 (Material:HDPE6060).

sharper with increasing screw speed. The throughput, Q, is the dominant factor determining the shape of the RTD.

The experimentally obtained RRDs are shown in Figure 6. These figures indicate that RRDs for operating conditions with the same specific throughput tend to be similar. A larger Q/N will result in a sharper RRD and smaller screw-revolution delay.

The experimentally obtained RVDs for the two-screw configurations are shown in Figure 7. Although small differences between the height of RTDs exist in the mixing zone, the differences are decreased at the die. When the RVD curves are shifted such that zero volume is defined when the first tracer is sensed by probe, rather than when the tracer was added, all the RVDs at the die superpose on each other, as shown in Figures 8 and 9. This indicates that the shape of the RVDs for a specific screw configuration does not change with the operating conditions. The differences between Figures 8 and 9 suggest that the axial distribution of the tracer is more sensitive to changes in screw configuration than the operating conditions Q and N.

Investigation of the RVD and RRD gives physical insight into the factors affecting the extrusion process. The RVDs and RRDs obtained at the die for the first screw configuration shown by Figures 6 and 7 reveals the following features of the extrusion process.

- For operating conditions with the same specific throughput, the RVDs or RRDs tend to be the same. The specific throughput (Q/N) is an estimate of the degree of fill in the partially filled sections, which then affects the delay time and the shape of RTD. For different operating conditions with the same specific throughput and material viscosity, the degree of fill at a specific position of the screw tends to be the same, which results in the same RVD and RRD, as shown by the data. This result needs to be interpreted against the fact that the rheology changes with screw speed.
- For a given screw geometry, the shapes of the RVD (that is, after subtraction of the volume delay) for all the operating

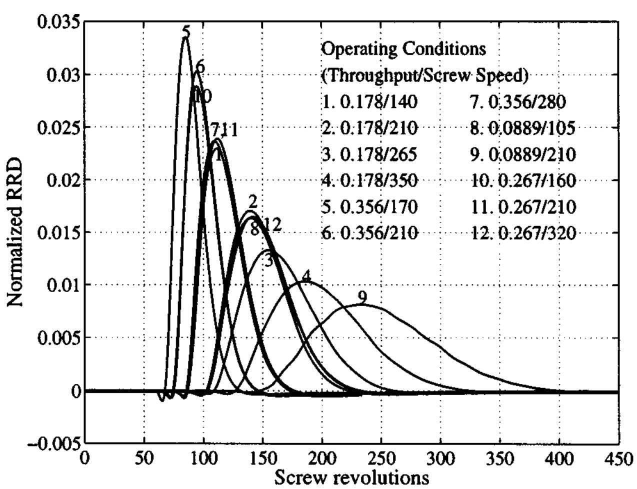

Figure 6. RRD at the die for screw configuration 1 (Material:HDPE6060).

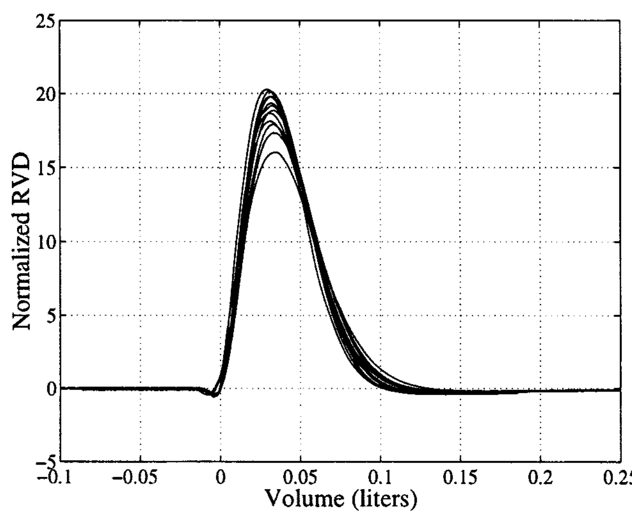

Figure 8. Overlapped RVDs at the die for screw configuration 1 (Material:HDPE6060).

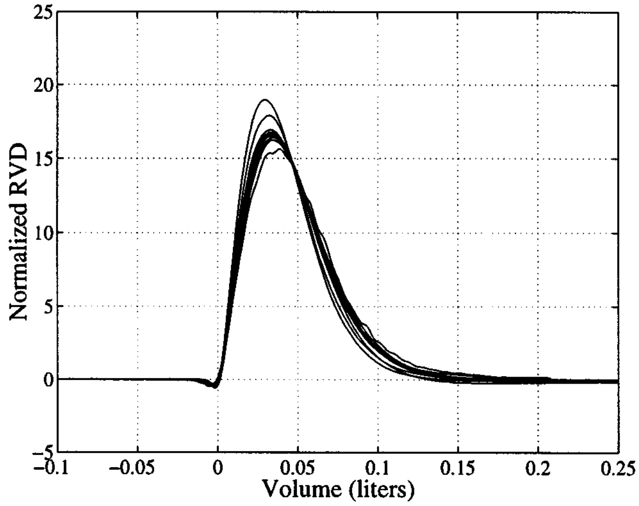

Figure 9. Overlapped RVDs at the die for screw configuration 2 (Material:HDPE6060).

conditions are essentially the same. This indicates that the axial distribution of the tracer material in the resultant extrudate is not a function of the operating conditions for a given screw geometry. This is an important observation and indicates that if the shape of the RVD is taken as a measure of the axial mixing power of the machine, then the only way to effectively change the RVD is to change screw geometries.

- The shape of the RTD is dominated by throughput. The RTDs at the die with the same throughput tend to be the same. Increasing the throughput with screw speed held constant will move the RTD toward shorter times and make the RTD sharper. Increasing the screw speed with throughput held constant will also move the RTD toward shorter times but without significantly changing in the shape of RTD.

- The specific throughput has an opposite effect on the delay volume and screw-revolution delay. A larger specific throughput will result in a larger delay volume and a smaller screw-revolution delay.

These four observations form the foundation for our RTD model. Although the partially filled region may mix the material to some extent, the contribution to mixing is much less than the fully filled region. If the partially filled screw sections are modeled by a delay time for simplification and the fully filled regions are modeled as a combination of a delay time and identical perfect mixers, then the profile of the RTD can be modeled by a simple functional form with a shape related to the RTD mean pulse time (Naor and Shinnar, 1963). Since the same throughput should result in similar RTD shapes, the RTD mean pulse time determined by the fully filled region should be similar for the same throughput.

The fourth feature of the RVD and the RRD shows that the delay time, which is due to both the partially filled regions and fully filled regions, should have a inverse relationship with the throughput and screw speed. With the delay time and mean pulse time determined, the RTD is also determined.

The Residence Distribution Models

Residence-time distribution model

The predictive RTD model developed in this article is described by the following equations:

$$f(t) = \frac{a^3}{2}(t - t_d)^2 e^{-a(t - t_d)}, \tag{4}$$

where

$$t_d = t_m - \frac{3}{a} \tag{5}$$

$$t_m = \frac{A}{Q} + \frac{B}{N} \tag{6}$$

$$A = A_f L_m + V_p \tag{7}$$

$$B = \frac{2 A_f L_c}{(2i-1)\pi D \cos\theta WHF_d} \tag{8}$$

$$a = CQ, \tag{9}$$

where t_m is the mean residence time, which has been studied by Gao et al. (1999), and a is the RTD shape factor that is determined by the throughput Q, and C is a constant that needs to be determined from experiment.

We begin the derivation of the model by considering the filled and partially filled zones in the extruder separately. The partially filled conveying sections can be modeled as delay-time elements. Following the literature (Bigio et al., 1992; Bigio and Conner, 1995; Thompson et al., 1995), the model assumes that any axial mixing effect in the partially filled conveying sections is negligible when compared to the fully filled sections. The model assumes that the distribution of the tracer along the extruder is mainly caused by the axial mixing from the three fully filled regions: the melting, mixing, and metering zones. To simplify the model, the contributions of these three fully filled regions to the RTD are modeled as a combination of a delay time and simple mixer vessels. Thus, the RTD function can be expressed by Eq. 4, and its shape is characterized by a shape factor, a, whose relationship to the mean pulse time is given by

$$a = \frac{3}{t_w}. \tag{10}$$

The delay times contributed by each of the different filled and partially filled sections constitute the total delay time, t_d, which can also be expressed as $t_m - t_w$, as is shown in Eq. 5. Based on the discussion of the features of the RVD, the mean pulse time should have an inverse relationship with the throughput, as is shown in Eq. 11:

$$t_w = \frac{3}{CQ}. \tag{11}$$

Combining Eqs. 10 and 11 results in Eq. 9. Substituting Eqs. 6 and 9 into Eq. 5, results in the relationship between the delay time, throughput, and screw speed shown by Eq. 12:

$$t_d = \frac{A - \dfrac{3}{C}}{Q} + \frac{B}{N}. \tag{12}$$

The constant C in Eq. 12 is unknown and can be determined from experiment. Equation 4 is fit to each of the twelve operating conditions for both screw geometries with t_d and a as floating parameters.

Residence-revolution distribution model

The RRD model can be derived from the definition of RRD function $h(n)$ in Eq. 2 using the following steps:

$$h(n) = \frac{c\left(\dfrac{n}{N}\right)}{\displaystyle\int_0^\infty \left| c\left(\dfrac{n}{N}\right) \right| dn} = \frac{e\left(\dfrac{n}{N}\right)}{N}$$

$$= \frac{a_n^3}{2}(n - n_d)^2 e^{-a_n(n-n_d)}, \tag{13}$$

where a_n is an RRD shape-control parameter and n_d is the screw-revolution delay given by

$$n_d = t_d \times N = B + \left(A - \frac{3}{C} \right) \frac{N}{Q} \tag{14}$$

$$a_n = \frac{a}{N} + C\frac{Q}{N}. \tag{15}$$

It is shown by Eq. 13 that the profile of RRD curve is determined by parameter a_n, while Eqs. 14 and 15 indicate that a_n and screw-revolution delay are determined by the specific throughput. Thus operating conditions that have the same specific throughput should have equivalent RRDs. As the specific throughput increases, Eq. 14 indicates that the screw-revolution delay will decrease.

Residence-volume distribution model

Similar to the derivation of RRD function, the RVD model can be derived with the following steps:

$$g(\upsilon) = \frac{c\left(\dfrac{\upsilon}{Q}\right)}{\displaystyle\int_0^\infty \left| c\left(\dfrac{\upsilon}{Q}\right) \right| d\upsilon} = \frac{e\left(\dfrac{\upsilon}{Q}\right)}{Q} = \frac{a_\upsilon^3}{2}(\upsilon - \upsilon_d)^2 e^{-a_\upsilon(\upsilon-\upsilon_d)}, \tag{16}$$

where υ_d is the delay volume given by

$$\upsilon_d = t_d \times Q = A - \frac{3}{C} + B\frac{Q}{N} \tag{17}$$

and

$$a_\upsilon = \frac{a}{Q} = C. \tag{18}$$

The preceding equations show that the shape of the RVD is determined by the parameter a_υ, which is a constant for a specific screw configuration. The shape of the RVDs for all the operating conditions using one screw configuration should be the same. The delay volume is an affine linear function of Q/N. A larger specific throughput will result in larger delay volume. For operating conditions that have the same specific throughput, the RVDs should be equivalent.

Model Validation

To validate a dynamical model one typically runs two sets of input−output experiments, identifies model parameters with the first, and tests to fit on the second. In our case, the inputs for fixed operating conditions are identical: a delta input of tracer material. Consequently the traditional validation tests will not reveal flaws in the model. We can, however, test two aspects of the model. First, we can test the fidelity of the family of RTD curves by finding the member of this family that is closest in a least-squares sense to the experimental data. If there are operating conditions where the best fit is poor, the RTD model chosen is inadequate. Second, we can test how well we can predict the model parameters as a function of operating conditions by comparing the best-fit parameters against the predicted parameters.

First note that the general trends predicted by our models are exhibited in the experimental data. From Eqs. 4 and 9, it can be seen that the shape of the RTD is modeled by parameter a, while a is affected only by throughput. The RTD shapes are expected to be similar for operating conditions having the same throughput. Equations 9 and 12 reveal that a larger throughput will result in a sharper RTD and smaller time delay, and a greater screw speed will move the RTDs toward shorter time. These features revealed by the model are consistent with the experimental result shown by Figure 5. In the RRD model, Eqs. 14 and 15 indicate that specific throughput is the only factor affecting the screw-revolution delay and the shape of RRD. For those operating conditions with the same Q/N, the model indicates that their RRD curves tend to be equivalent. Larger Q/N will result in sharper RRD and smaller screw-revolution delay. In the RVD model, the shape factor is a constant, and thus the shapes of all RVD curves for a given screw configuration and material viscosity are expected to be equivalent. These properties are verified by the experimental data.

Model parameter identification and RTD curve fitting

The model function given by Eqs. 4, 5 and 9 suggests that the RTD can be approximated by a function that contains two parameters: delay time and a shape factor. The delay time is an inverse hyperbolic function of screw speed and throughput, and the shape factor has a linear relation with throughput. In order to investigate how well this function can describe the RTD and to compare the relationships between the model parameter and operating conditions, a least-square fit of the optimal parameters of the function to the experimentally obtained RTD data was performed. The comparison between the experimental RTD plots for several operating conditions and the simulated RTDs calculated using the model are shown in Figures 10 and 11, with the dashed lines denoting the simulated RTD. The optimal model parame-

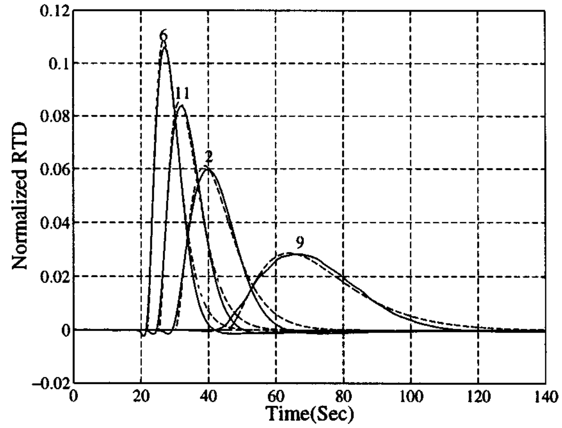

Figure 10. Original RTDs (——) vs. simulated RTDs (– – –) at the die for screw configuration 1 (Material:HDPE6060).

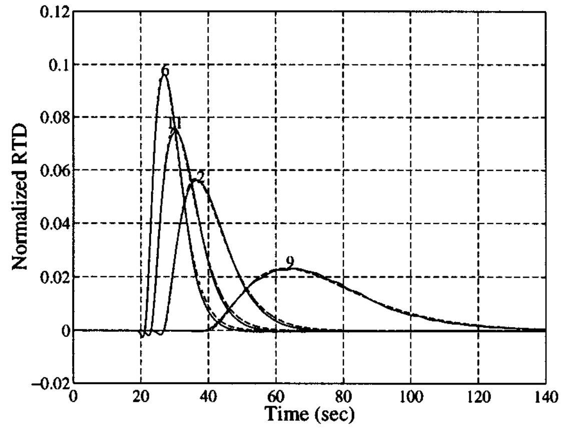

Figure 11. Original RTDs (——) vs. simulated RTDs (– – –) at the die for screw configuration 2 (Material:HDPE6060).

ters, as functions of throughput and screw speed, are listed in Table 2 and are expressed by three-dimensional surfaces shown in Figures 12 and 13. The delay-time surface is hyperbolic, while the shape factor appears to be a linear function of throughput, which is explained by the model.

Conclusions

The residence volume and residence screw-revolution distribution are introduced in this article. The data presented on the RVD and RRD indicate that specific throughput is a key factor determining the flow conditions in the screw ex-

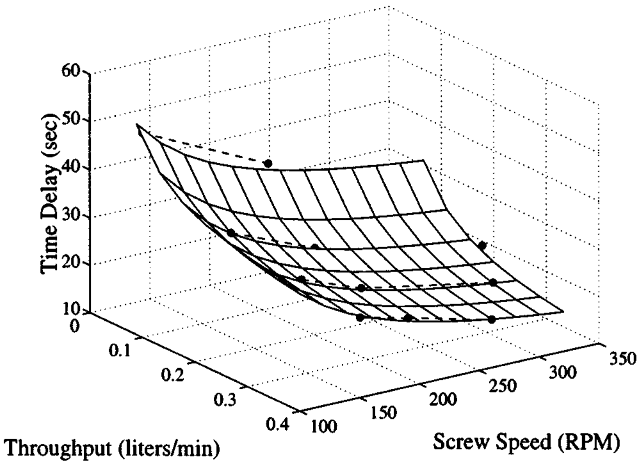

Figure 12. Delay time at the die as a function of screw speed and throughput for screw configuration 2 (Material:HDPE6060).

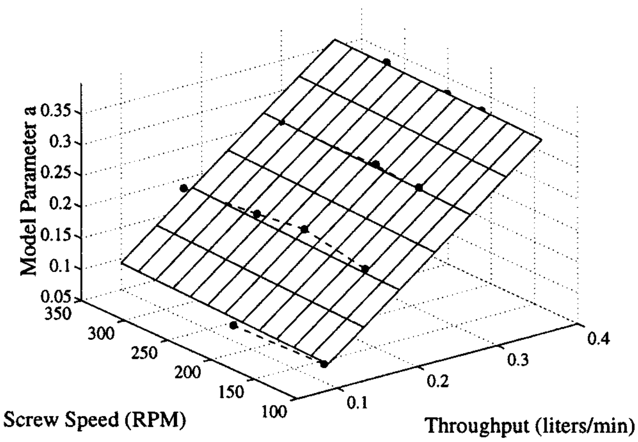

Figure 13. Shape factor at the die as a function of screw speed and throughput for screw configuration 2 (Material:HDPE6060).

truder, and the same specific throughput will result in the same RVD and RRD. It is shown that the physical distribution of tracer along the axial direction of the extrudate does not change significantly for a given screw configuration and that changing the screw configuration is a more feasible way to change the axial distribution of material. The discussion on the characteristics of RVD and RRD lead to the development of a physically motivated predictive RTD model that can be used to explain the effect of screw speed and throughput on the RTD. The model predicts that higher screw speeds

Table 2. Experimentally Determined Model Parameters for Screws and Operating Conditions

Operating Condition		1	2	3	4	5	6	7	8	9	10	11	12
Screw 1	t_d	37.3	30.0	25.2	22.2	24.1	21.8	18.4	60.0	45.1	28.2	25.1	19.9
	$a \times 10$	2.07	2.26	2.21	2.27	3.62	4.01	4.19	1.08	1.06	2.95	3.16	3.30
Screw 2	t_d	33.8	26.6	22.8	19.0	23.5	21.1	16.8	52.1	39.6	27.5	22.8	17.6
	$a \times 10$	1.91	2.10	1.99	1.85	3.58	3.61	3.67	9.01	8.57	2.74	2.80	2.79

and larger throughputs result in a smaller delay time, and different screw speeds with the same throughput will result in RTDs of similar shape. A least-squares error fit method is used to identify the parameters of the RTD model, and it is indicated that the model function is appropriate to describe the RTD experimental data.

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