Residence Time Distributions in a Plasticating Twin Screw Extruder

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Residence time distribution measurements in a twin screw extruder are compared with a model based on ideally mixed chambers. Special attention is given to the tail of the distribution. These measurements are compared with the residence time distributions in single screw extruders and an empty pipe.

SCOPE

Although more and more twin screw extruders are being used in the polymer industry, there are still few investigations published. Not only for normal polymer extrusion but especially for the use of the extruder as a chemical reactor, the knowledge of the residence time distribution is important.

In order to investigate residence time distributions in a plasticating twin screw extruder, experiments have been performed by means of a radioactive method. At a certain time ($t = 0$), a pulse of manganese dioxide was imposed on the extruder. Samples which were taken at the outlet were irradiated with thermal neutrons, and the induced radioactivity of ^{56}Mn decaying to ^{56}Fe was measured. This method gives a good reproducibility over three decades in concentration, and an extended tail in residence time distributions could be measured. The measurements are compared with a theoretical model in which fully filled chambers are assumed and with measurements and a theoretical model of a single screw extruder.

The knowledge of the spread in residence times in an extruder is important. It indicates how long a certain part of the material is exposed to a certain heat load and shear. A combination of this heat load and shear and the time of exposure gives, together with the amount of stabilizer, an indication of the degradation (Ingen-Housz, 1976). A new area, so far hardly developed in which the knowledge of the residence time distribution is important, is the use of a twin screw extruder as a chemical reactor. The only information reported on this kind of application is for bulk polymerization, where the post condensation time can be reduced by a factor of six compared with the usual equipment (Mack, 1972). Only the molecular weight distribution is largely affected by the spread in residence times of the reacting materials in the equipment.

CONCLUSIONS AND SIGNIFICANCE

In this paper, the residence time distribution in a counterrotating, closely intermeshing, twin screw extruder is investigated and compared with a model in which the chambers in the extruder are assumed to be well mixed.

The mean residence times as well as the residence time distributions are remarkably stable. The mean residence times are within reasonable limits independent of operating changes and are in good agreement with the theoretical values. There is only a slight influence of the die pressure on the tail of the dimensionless residence time distributions. Results of computational models based on a series of ideally mixed chambers must be regarded with extreme care, since the nonlinearity in the log-linear representation of the distribution functions implies a limited amount of mixing within the extruder. Especially when the tail of the distributions is regarded, conclusions from these models might well be erroneous.

Although twin screw extruders appear more and more in industry, the knowledge of the phenomena that control the working of these machines is still poor.

Over the years, single screw extrusion has been thoroughly investigated, and its working is now well understood. The major difference between a single screw extruder and a twin screw extruder lies in the mechanism of transportation. A single screw extruder has one screw in a closely fitting barrel. Transportation is only possible when there is a friction at the barrel surface. It is easy to understand that if the process material sticks to the screw and slips at the barrel surface, there will be no output from the extruder because the material rotates with the screw without being pushed forward. In a twin screw extruder, two parallel screws are placed in a figure of eight section barrel. The objective was to overcome the effects of the slip at the wall. Generally speaking, the extruders can be divided into two major categories of intermeshing and nonintermeshing screws. These categories can be subdivided into extruders in which the screws rotate in the same or opposite direction (corotating and counter-

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rotating, respectively). We will restrict ourselves to extruders with intermeshing counterrotating screws. This implies that more or less C shaped chambers are present that positively convey the process material to the die end of the extruder. Thus, slip at the wall becomes irrelevant, since the intermeshing part of one screw prevents the material in the other screw rotating freely.

Twin screw extruders are often claimed to have good flow, mixing, and residence time distribution characteristics, but there have been few published investigations. Todd (1975) has measured residence time distributions with polybutenes, using methylene blue as a tracer. Since methylene blue is completely insoluble in polybutenes, it can be leached out with water, allowing an estimate of the integral of the tail of the residence time distribution curve.

Todd and Irving (1969) also presented experiments done with glucose solutions with potassium nitrate and sodium nitrate added. The residence times were determined in that case from conductivity measurements.

Janssen and Smith (1975) reported on measurements of mixing and residence time distributions in a model extruder completely filled with Newtonian liquid. However, all these measurements are performed with model liquids, not taking into account the complete extrusion process.

THEORY

In a twin extruder, four distinct zones can be distinguished (Janssen et al., 1976; Janssen, 1978). These are from hopper to die: a solid transport zone, a melt zone, a zone where the polymer is fully molten but the chambers are only partially filled, and a pump zone, where the C shaped chambers are fully filled and where pressure is built up.

Schenkel (1966) stated that the idealized theoretical output from the fully filled pump zone is the number of C shaped chambers becoming free per unit time multiplied by the volume of one chamber. This gives for a twin screw extruder with m thread starts per screw

$$Q_{th} = 2\, m\, N\, V \tag{1}$$

Because of the existence of leakage gaps, the output is in practice less than this ideal value. In previous work (Janssen et al., 1975; Janssen and Smith, 1976; Janssen et al., 1976; Janssen, 1978) the significance of these leakage gaps for the transport and pressure buildup have been discussed, and a comparison between analytical solutions for the flow and measurements has been given. Summarizing, we can distinguish four different leakages (Figure 1):

1. The leak (Q_f) through the gap between the flight and the barrel wall (flight leak). This leakage is somewhat similar to that in a single screw extruder.

2. The leak (Q_c) between the bottom of the channel of one screw and the flight of the other screw (calender leak).

3. The leak (Q_t) through the gap that goes from one screw to the other between the flanks of the flights of the two screws (tetrahedron leak).

4. The leak (Q_s) through the gap between the flanks of the screws perpendicular to the plane through the screw axis (side leak).

These four leakage flows are mainly responsible for the spread in residence times, since if there were no leakage flows at all, the material entering the extruder at the same moment would be collected in one chamber, transported together, and discharged at the outlet of the extruder at approximately the same time. In that case, the spread in residence times would be very limited and only determined by the mixing within one C shaped chamber and the outlet channel.

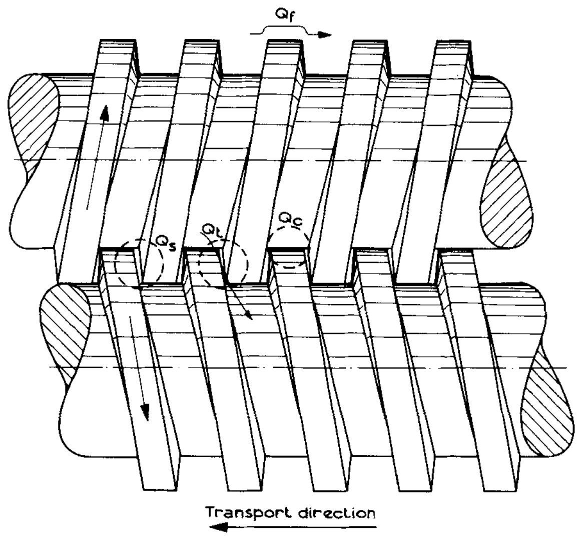

Fig. 1. Various leakage flows in the extruder.

However, these leakages are only important in the pump zone of the extruder. In the first three zones, there is no pressure build up (Janssen et al., 1976); therefore, the leakages are negligible, and the flow in these zones can be assumed to be plug flow.

Residence time distributions can be used in characterizing the overall mixing in an apparatus. Fluid elements entering the extruder simultaneously will generally leave it at different times. This distribution in residence time can be described quantitatively with two functions which are closely related, the exit age distribution and the internal age distribution. The response of an apparatus to a pulse at the inlet is given by the exit age distribution, which represents the age distribution of the fluid leaving the apparatus.

In processes where time dependent degradation and self-cleaning action are important, for instance in most extrusion processes, it is convenient to know how long one must wait until there is only a certain fraction of the initial material in the machine. This can be described with the internal age distribution $(1 - F)$ which is related to the exit age distribution E by

$$1 - F = \int_{\theta}^{\infty} E(\theta)\, d\theta = 1 - \int_{0}^{\theta} E d\theta \tag{2}$$

where $\theta \equiv t/\tau$ and $\tau = V_f/Q_v$. This internal age distribution is most convenient in characterizing an apparatus. When the tail of the residence time distribution is especially important, as it is in extrusion technology, a semilogarithmic plot of this function can be used. Since a semilogarithmic plot of the internal age distribution of a perfectly mixed tank is a straight line, deviations from a straight line can sometimes be used as a criterion for imperfectness of the mixing process.

The actual filled volume is important for the calculation of the residence times. In twin screw extruders, the feed end of the screws is partially empty, and only the die end is fully filled with material. Since the leakage flows in the partially filled length of the screws can be neglected, the degree of filling of the first extruder part can be calculated directly as the ratio between the real volumetric throughput and the maximal theoretical throughput given in Equation (1):

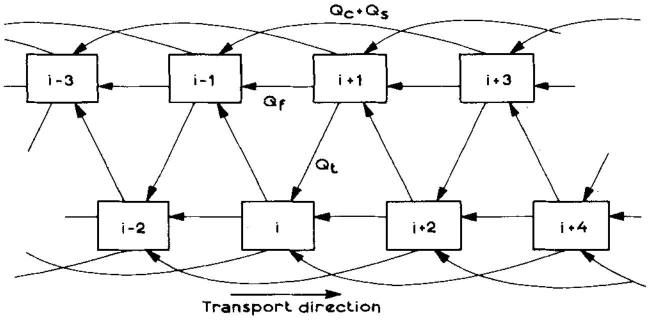

Fig. 2. Model for a twin screw extruder with double thread start screws.

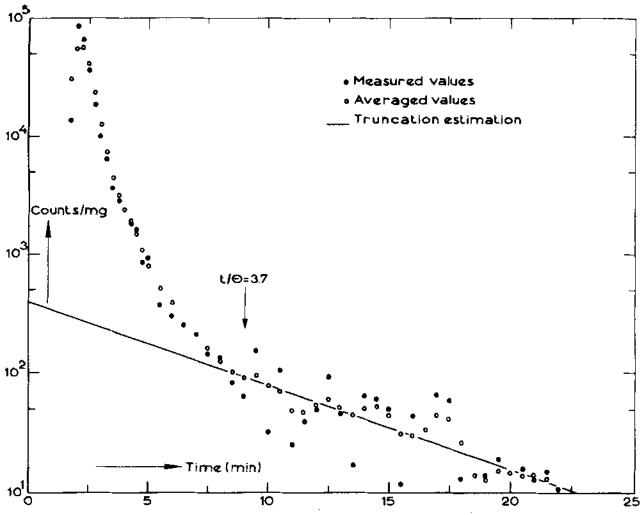

Fig. 3. Determination of the truncation error.

$$u = \frac{Q_v}{2NmV} = \frac{Q_m}{2NmV\rho} \qquad (3)$$

If the number of chambers of the fully filled zone ν_F is known, the total filled volume for a uniform screw can be calculated from

$$V_f = V\,[(\nu_T - \nu_F)\,u + \nu_F] + V_d \qquad (4)$$

If there are zones in the extruder where the screws have a different geometry or if the material density ρ_i cannot be assumed constant, this formula can be modified and gives, together with Equation (3)

$$V_f = V_d + \sum_{i=1}^{\nu_T} \frac{Q_m}{2Nm_i\rho_i}\,\Omega_i + V_i\,(1 - \Omega_i) \qquad (5)$$

where i is the number of the chamber observed, and Ω_i is zero for fully filled chambers and unity when the chambers are partially empty.

Since the mean residence time is defined as the ratio between filled volume and volumetric throughput, if constant material density is assumed, we obtain

$$\tau = \frac{V_d}{Q_v} + \sum_{i=1}^{\nu_T} \frac{\Omega_i}{2Nm_i} + \frac{V_i(1 - \Omega_i)}{Q_v} \qquad (6)$$

The distribution of residence times can also be computed. If the chambers are assumed to be ideally mixed, a series of differential equations can be formulated for the fully filled zone of the extruder, where the leakages provide the in and outflows. This is for double flighted screws (see Figure 2):

$$V\frac{dC_i}{dt} = (Q_c + Q_s)C_{i+4} + Q_f\,C_{i+2} + Q_t\,C_{i+1}$$

$$- (Q_c + Q_s + Q_f + Q_t)C_i \qquad (7)$$

$$i = \nu_T - \nu_F + 1,\quad \nu_T - \nu_F + 2,\quad \ldots, \nu_T - 4$$

For the part of the extruder where the chambers are not fully filled, that is, for chambers with a number lower than ν_F, plug flow is assumed. The equations for the last four chambers are modified in such a way that the leakage flows return from the die instead of from a nonexisting chamber.

Since the chambers in the extruder move from hopper to die, after each revolution time a number of chambers equal to twice the number of thread starts per screw is added at the hopper end of the extruder, and an equal number of chambers is removed at the die end. In this way, the exit age distribution of a plasticating twin screw extruder can be calculated numerically. The results obtained from this calculation, using the assumption that each chamber is perfectly mixed with the incoming leakage flows on each revolution, provides a comparative basis for experimental work below.

In this model, the influence of temperature gradients and the associated viscosity changes are included in the calculations of the various leakages. However, because of continuity, the total amount of leakage is constant throughout the fully filled zone (Janssen et al., 1976). Therefore, no significant influence of a temperature gradient on the residence time distribution has to be expected.

TRUNCATION ESTIMATION

An important question in any kind of residence time distribution experiment is how much tracer is left in the apparatus after the last sample is taken, or what is the truncation error? Generally this question can be answered by extracting the tracer from the total content of the apparatus after the last sample has been taken, or by fulfilling a mass balance over the whole experiment. In this experiment, this was not possible, since manganese dioxide is hard to extract from polypropylene, and the problem for fulfilling the mass balance was the uncertainty in the flux of irradiation of the samples.

Still, it is important to know the truncation error, since the internal age distribution is sensitive to it.

Todd (1975) suggested a method for estimating the truncation error. In general, a plot of the individual tracer concentrations tend to tail off as a straight line on semilogarithmic paper (Figure 3). This straight line can be written as

$$C = K\,e^{-a\theta} \qquad (8)$$

If the last measured concentration C_e was made at time $= \theta_e$, the truncation error (R) can be calculated from

$$R = \int^{\infty} K\,e^{-a\theta}\,d\theta = \frac{K}{a}\,e^{-a\theta_e} \qquad (9)$$

Since

$$C_e = K\,e^{-a\theta_e} \qquad (10)$$

$$R = \frac{C_e}{a} \qquad (11)$$

Thus, the truncation error can easily be estimated by dividing the value of the last point by the slope of the estimated tail in a semilogarithmic plot. This method can be applied to estimate where to stop taking samples if a certain error is acceptable. In practice, most measurements are stopped when the signal to noise ratio is too small. To obtain a good estimation of the tail of the residence time distribution, that is, the slope of the linear part of the logarithmic plot mentioned before, it is im-

TABLE 1. INFLUENCE OF CORRECTION OF THE INTEGRAL FOR THE TAIL OF THE RESIDENCE TIME DISTRIBUTION CURVE

Error without correction	Average error after correction
1.16%	0.45%
1.17%	0.82%
1.00%	0.03%

portant that the spread in measurements at the end of the curve is small. A method of weighted averages was applied for the values in the tail of the residence time distribution to smooth it out in order to obtain a good estimation of the slope of the extrapolation line (Figure 3).

To achieve some information about the accuracy of this method, three measurement series were performed with extreme care and the time over which samples were taken extended to nearly 1 hr. In these series, the integral of the total exit age distribution was computed twice, once with measurements up to 25 min and once with all measurements. In a log-linear plot of only the first part of the measurement (up to 25 min), a reasonable truncation estimation was drawn by several people without knowledge of the rest of the curve. With these lines, the total surface was calculated and compared with the computed integral over the whole series of measurements. Table 1 shows the results. The first column gives the relative difference between the computed values of the integral over the whole series up to 56 min and the integral up to 25 min. This can be assumed to be an approximation of the relative error made when the truncation estimation is neglected. The second column gives the relative difference between the integral over the total curve and the integral over the truncated series after correction for the truncation error. It can be seen that application of this correction for the truncation error improves the accuracy of the residence time distribution curve.

MEASUREMENT TECHNIQUE

In order to determine the residence time distribution of a twin screw extruder, a pulse of tracer material was supplied at the input, and the concentration of tracer material was measured at the output as a function of time. The input pulse used consisted of 4 g polypropylene, doped with 5% (weight) inactive manganese dioxide. When the extrusion process had become stationary, the pulse was fed symmetrically into two chambers, one in each screw, at the very moment that the hopper had become empty. The hopper was immediately filled up with normal undoped polypropene after the pulse was applied.

Samples were taken from the output at time intervals ranging from ¼ to 1 min. To determine the manganese dioxide concentration, the samples were irradiated in the Delft Research Reactor HOR with thermal neutrons, and the induced radioactivity of ^{56}Mn decaying to ^{56}Fe was measured.

The fully automatized data analysis was carried out on a DEC PDP-9 computer. The computer output consists of an exit age distribution (E) and an internal age distribution (1 − F) for each measurement series.

SAMPLE PREPARATION AND IRRADIATION

The doped polypropene was made by extruding the same polypropene in several cycles in a small laboratory single screw extruder. A gradual increase of manganese dioxide concentration was necessary, since the extruder gave no output when all the 5% manganese dioxide powder was added at the same time because of slip at the extruder barrel surface. Once the manganese dioxide was embedded in the polypropene, no slip was detected.

Since very low manganese dioxide concentrations have to be measured, it is necessary to avoid contamination of the samples with manganese containing materials, such as steel, from the moment that the tracer pulse is applied at the extruder till the samples have been irradiated. The extruder adds a negligible quantity of manganese to the polypropene as appeared from a test measurement. Titanium scissors and tweezers were used to cut and handle the samples. The samples were taken immediately after the die by pressing the hot polypropene between two glass plates and cutting the plates at the glass edges. The flat samples thus formed have several advantages. They can be cut even after the polypropene has cooled off, they can be marked easily, and they can be packed very compactly. Small strips (about 50 mg) were used when the manganese dioxide concentration was high, and larger ones (up to 400 mg) were used for low manganese dioxide concentrations. All strips were taken in such a way that a mean concentration over the total diameter of the original output stream at the die was measured. The samples were weighed and marked by writing numbers on them with a nonactivating ink. All samples from one experiment were packed randomly together in aluminum foil in a small (15 × 15 × 50 mm) package to avoid the influence of the flux gradient, and irradiated for 2 min at a flux of 10^{13} thermal neutrons/cm²/s.

DETECTION SETUP

After a 3 hr cooling down period, the activated samples were put in separate bottles in an automatic sample changer. The measurement, beginning with the last low concentration sample, started about 4 hr after the irradiation.

This reversed order was chosen to combine good counting statistics for the weakly activated samples with a measuring range of about 4 decades.

The gamma radiation from the decay of ^{56}Mn to ^{56}Fe was measured with a detector consisting of a well type NaI(Tl) scintillation crystal optically coupled with a photomultiplier. The detector was mounted in a low background assembly of old lead.

From each sample, a partial gamma spectrum was taken with a 512 channel multichannel analyzer. The chosen energy range corresponds with an absorbed energy per photon of about 650 to 1 050 keV. This energy selection gives a well-distinguishable peak at 847 keV on a relative low and flat background.

ACTIVATION ANALYSIS

The analyzer memory contents were read out on paper tape and later on magnetic tape. The starting times of the measurements, sample weights, and the sample times were also stored on magnetic tape. With a computer program from each spectrum, the peak position, peak width, and the number of counts in the total absorption peak at 847 keV from the decay of ^{56}Mn were calculated. These peak contents were corrected for the background. The background was determined from the same spectrum at the lower and the higher energy side of the 847 keV peak. The mean value from both sides was used.

These intermediate results have to be corrected for sample weight and radioactive decay. However, it also has to be taken into account that some 847 keV photons that are absorbed in the scintillation crystal are not stored in the 847 keV peak.

Summation

In 47% of all cases, a 847 keV photon from a nucleus is accompanied by a photon of 1 811, 2 110, or 2 520 keV, emitted by the same nucleus at almost the same time.

Pileup

Two nuclei in one sample might decay very shortly after one another. The amplifiers and multichannel analyzer have a time resolution of only about 1 μs. Within such a time interval, the measuring system cannot distinguish between one or two absorbtions.

The losses due to this effect were calibrated for all the amplifier and analyzer settings used for various source strengths under real measuring conditions.

After the corrections for sample weight, radioactive decay, summing, and pileup for each sample, a number is obtained that is proportional to the manganese-dioxide concentration in that sample. These numbers were stored on magnetic tape and were used in a second computer program to calculate and construct the exit age distribution and the internal age distribuetion.

RESULTS

In order to assess the accuracy of the measurements, the reproducibility of the method adopted has been investigated in four different measurement series. From these series, an insight can be obtained into three possible sources of error:

1. The distribution of the manganese dioxide. Each sample of one series was cut in half and the results of both parts compared.
2. The irradiation in the nuclear reactor. One series was irradiated twice with several days in between.
3. The reproducibility of the extruder. Two different measurement series made in the same extruder with the same operating conditions were investigated.

Figure 4 shows the reproducibility measurements as a semilogarithmic plot of exit age distribution vs. dimensionless time. It can be seen that even at extremely low concentrations the spread is reasonable and that there are no large differences between the various measurement series. Only in the tail of the curve does the spread become significant. This spread is generally due to agglomeration of the manganese dioxide particles. The most extreme case of this can be seen from the high open triangle point at $\theta = 3$, which was one half of a sample, and the related point (black dot), which was the other half of the sample. The corresponding values for the E function within the same sample were 0.035 and 0.012. Examination of the extrudate under a microscope showed agglomerations of the tracer material larger than those found in the original powder. Such agglomerations give rise to statistical fluctuations in the measurements of the tail of the residence time distribution. The influence of pressure, screw rotation, and temperature on the mean

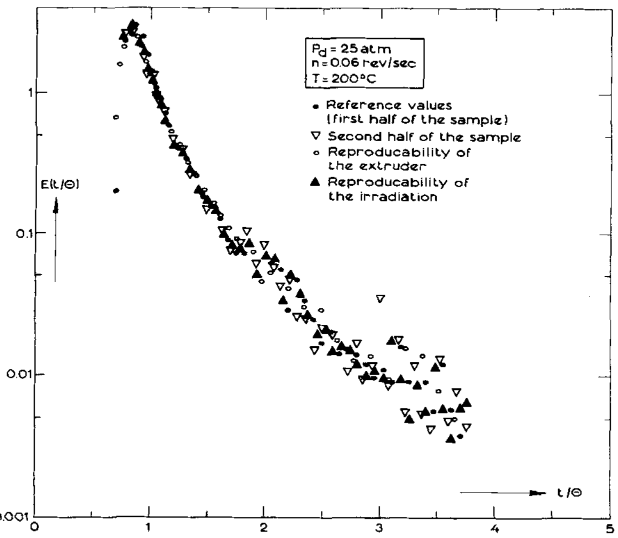

Fig. 4. Reproducibility measurements.

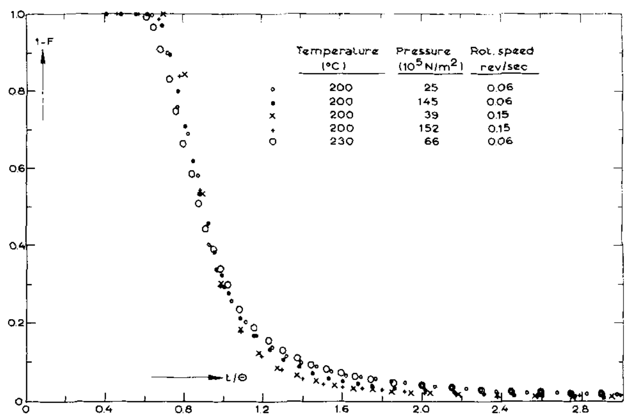

Fig. 5. Exit age distribution versus dimensionless time for various operating conditions.

TABLE 2. MEASURED MEAN RESIDENCE TIME (τ), CALCULATED MEAN RESIDENCE TIME (τ_{calc}), AND DIMENSIONLESS MEAN RESIDENCE TIME ($\tau.N$)

	$N = 3.6$ rev/min			$N = 6.0$ rev/min			$N = 9.5$ rev/min		
Low pressure	404		24.3	230		23.3	143		24.8
$T_b = 200°C$		404			233			157	
	25		31	35		28	40		26
Medium pressure	429		24.0	244		25.1	144		22.8
$T_b = 200°C$		400			251			144	
	76		37	91		31	63		27
High pressure	386		24.2	255		25.1	148		23.0
$T_b = 200°C$		403			251			145	
	148		39	150		36	155		34
Medium pressure	405		24.3						
$T_b = 230°C$		401							
	67		39						

KEY

$\tau_{calc}(s)$		$\tau.N$
	$\tau(s)$	
$P_d(10^6\ N/m^2)$		ν_F

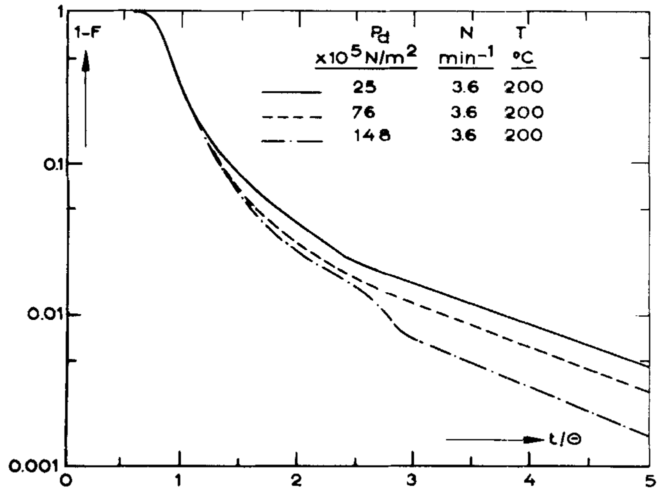

Fig. 6. The influence of the die pressure on the tail of the residence time distribution at low rotational speed.

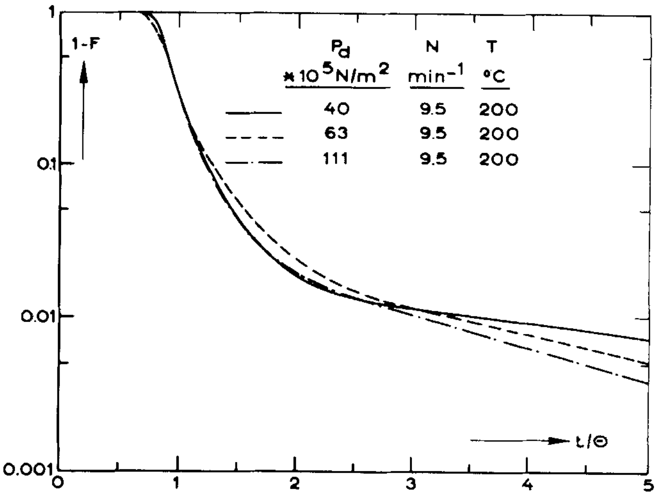

Fig. 7. The influence of the die pressure on the tail of the residence time distribution at high rotational speed.

residence times is shown in Table 2. It can be seen that the measured mean residence times are in good agreement with those calculated from Equation (6). When these mean residence times are made dimensionless by multiplication by the screw speed, they are within reasonable limits independent of die pressure, screw rotation speed, and barrel temperature; this is associated with the relatively small change in the number of fully filled chambers.

After we normalize the residence time distribution by making the area under the C function equal to unity, the F function can be obtained by integration. This is shown in Figure 5, where the internal age distribution is plotted against the dimensionless time. It can be seen that also in the distribution of residence times the extruder is remarkably stable over its whole operating range.

It is interesting to plot the internal age distributions logarithmically to distinguish the effects of the operating conditions on the tail, as is shown in Figures 6 and 7. From these logarithmic plots, it can be seen that there is a tendency of the tail to become shorter at higher die pressures which was not visible at the linear representation. This statement also holds when the internal age distributions are extrapolated exponentially. No significant correlation has been found for the effect of variations in rotational speed when plotted in a dimensionless form.

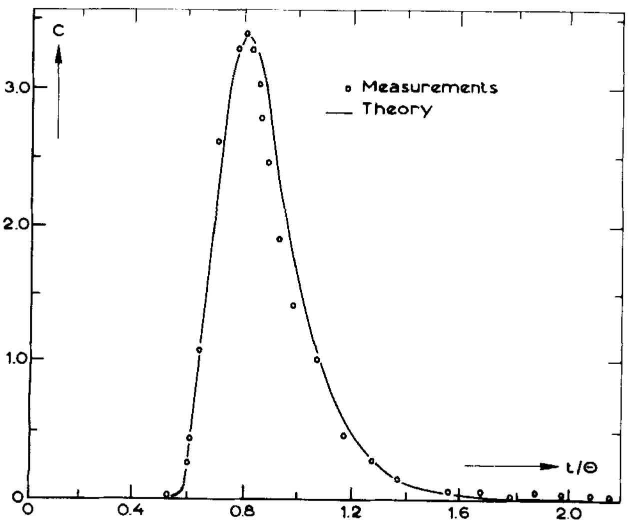

Fig. 8. Comparison between measurements and theory on a linear scale.

COMPARISON OF SOME DISTRIBUTIONS

A comparison between the measured response of the plasticating extruder and the theory is given in Figure 8. The computed values are corrected for the residence times in the (circular) die. A good agreement between theory and experiments can be seen on this linear scale. Nevertheless, when particular attention has to be paid to the tail of the distribution, as is generally true in extrusion technology, this graph should be plotted on a log-linear scale (Figure 9). While the theory tends to fall off in a straight line, the experiments show a clear and distinct tail. From the form of the experimental curve, it can be deduced that the material in the chambers of the extruder is not ideally mixed. This means that there is at least partial segregation of the material in the chambers, since a model built on the assumption of ideally mixed identical tanks with leakage flows between them will not give a kink in the E function when plotted logarithmically. The experiments of Todd (1975) show similar nonlinearity when plotted on log-linear axes and also do not agree with a model based on ideally mixed identical chambers. Flow experiments with a model extruder (Janssen and Smith, 1975; Janssen, 1978) also support the idea that mixing within individual chambers may be far from perfect.

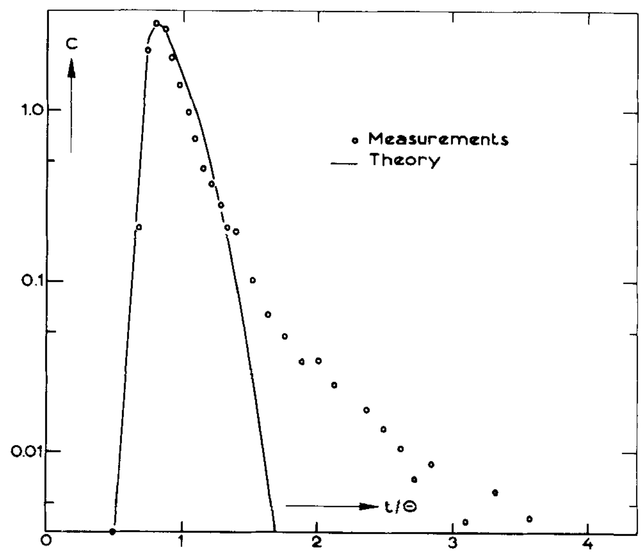

Fig. 9. Comparison between measurements and theory on a log-linear scale.

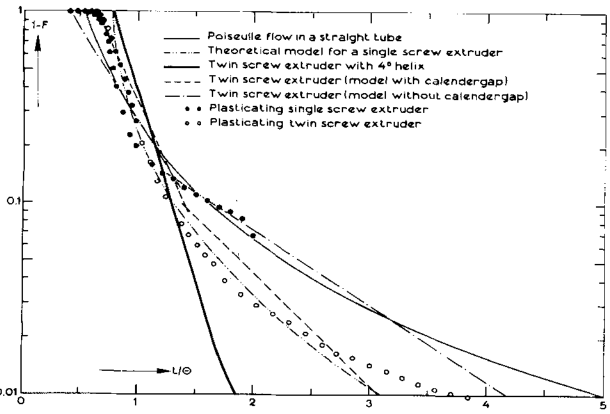

Fig. 10. Comparison of some dimensionless exit age distribution (log-linear scale).

At this stage it is interesting to compare some exit age distributions. Janssen and Smith (1975) have described measurements on a model extruder fully filled with a Newtonian fluid. Todd (1975) and Todd and Irving (1965) have made measurements with a starving twin screw extruder with different screw geometries. Pinto and Tadmor (1970) have developed a model calculation for fully filled single screw extruders, which has subsequently been verified by other authors (for example, Bigg and Middleman, 1974; Wolf and White, 1976). A useful comparison can also be made with the dimensionless exit age distributions corresponding to Poiseuille flow in a straight tube. Figure 10 summarizes all the results. It can be seen that the spread in residence times in the fully filled model extruders is greater than that in the plasticating extruder. This is quite natural, since in the real extruder the transportation in the solid transport zone is more or less plug flow, which diminishes the overall spread in residence times when plotted in dimensionless terms. It is also interesting to note that although the experimental exit age distribution of a plasticating twin screw extruder does not differ very much from the distribution calculated for a single screw extruder, it is markedly better than the experimental values found for a plasticating single screw extruder. Only when screws with very small helix angles are used can the spread be kept to a minimal value, as Todd (1975) has shown experimentally.

CONCLUSIONS

From the shape of a log-linear plot of the exit age distributions in model experiments, as well as in experiments with a plasticating twin screw extruder, it appears that computational models based on a series of ideally mixed identical chambers are erroneous since the nonlinearity in the log-linear representation of these exit age distributions implies a limited amount of mixing within the extruder. From the model experiments (Janssen and Smith, 1975) it has been seen that the nonlinearity is less with larger calender gaps or, on the other hand, with greater pressure gradients over the fully filled part of the extruder. A counterrotating, closely intermeshing, plasticating twin screw extruder has remarkably stable residence time characteristics. Expressed dimensionlessly by multiplying by the rotational speed of the screws, the mean residence times are independent of operating changes (within reasonable limits), with relatively small changes in the number of fully filled chambers. There tends to be a slight influence of die pressure in the tail of the dimensionless exit age distribution which can be seen in the shortening of the curve under these conditions.

NOTATION

a = slope of the estimated tail (log-linear plot)
c = concentration, kg/m^3
c' = corrected concentration, kg/m^3
c_e = last measured concentration, kg/m^3
i = counting variable
k = constant
m = number of thread starts per screw
n = counting variable
N = rotation rate, s^{-1}
P_d = die pressure, Pa
Q_c = calender leak, m^3/s
Q_f = flight leak, m^3/s
Q_m = mass flow, kg/s
Q_s = side leak, m^3/s
Q_t = tetrahedron leak, m^3/s
Q_{th} = theoretical throughput, m^3/s
Q_v = volumetric throughput, m^3/s
t = time, s
T = temperature, °C
u = degree of filling
V = chamber volume, m^3
V_d = volume of the die, m^3
V_f = filled volume, m^3

Greek Letters

θ = dimensionless time
θ_e = dimensionless time of last measurement
ν_F = number of fully filled chambers
ν_T = total number of chambers
ρ = density, kg/m^3
Ω = step function
τ = residence time, s

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