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Local residence time distributions in an intermeshing corotating twin screw extruder

M. Mercier¹, B. Zusatz¹, S. Hoppe¹, T. Vivier², G.H. Hu¹, F. Pla¹

¹ Laboratoire des Sciences du Génie Chimique
1 rue Grandville BP451-54001 Nancy Cedex France

² CERDATO, Atofina 27470 Serquigny, France

Keywords:

Residence time distribution, on-line fluorescent detection, convolution, statistical theory, extruder

Abstract

This paper deals with the local residence time distributions (RTD) in an intermeshing corotating twin screw extruder and shows their interest.

The RTDs were measured in three zones of the extruder and tracer was injected at different locations. Optical fiber probes are used in order to obtain real-time measurements of fluorescence radiation during extrusion of polyethylene HDPE and fluorescent particles of anthracene.

First, experiments were carried out to measure local residence time distributions in different processing conditions and to determine the quality of mixing thanks to the specific throughput.

Then, the convolution theory was verified by comparing the convolution of local RTDs functions to the overall RTD.

Finally, a predictive RTD model for twin screw elements based on the flow analysis of the individual screw zones and their statistical superpositions was developed.

Introduction

Because of the flow complexity in a twin screw extruder, the experimental determination of the residence time distribution (RTD) is a relevant choice. It enables to evaluate material flow, quality of product, efficiency of chemical reaction and mixing performance.

Since decades, lots of experimental methods have been used to determine RTDs. In the literature, many authors only measured the overall RTD. In this paper, an efficient on-line method to characterize the flow in local zones is presented.

The mean residence time and the variance of RTD functions give interesting information to investigate the influence of operating conditions (throughput, screw speed) on the mixing quality.

In the present paper, the RTD functions of independent sections of the extruder are numerically convoluted and compared to the overall RTD function. The convolution theory enables to determine RTD functions corresponding to each independent section of the extruder despite some possible measurement difficulties.

To understand the flow behaviour, numerous models have been developed. We propose to develop a predictive model based on the statistical theory introduced by Chen et al., 1993a, 1993b. The model was validated for a non intermeshing counter-rotating twin screw extruder by Chen et al. (1995) upon considering C-chambers as independent elements. The RTD of each element was calculated based on the work of Janssen, et al. (1979). We propose to adapt it to an intermeshing corotating twin screw extruder. The overall RTD is the convolution of individual elements to be defined.

Theoretical backgrounds

A few words about the RTD functions

The RTD can be described quantitatively using the function, $f(t)$, introduced by Danckwerts (1953).

$f(t).dt$ represents the fraction, at the exit, of flow that has been in the extruder during a period comprised between t and $t +dt$.

It can be evaluated thanks to the data of concentration vs. time and the following equations (Levenspiel, 1972):

$$f(t) = \frac{c(t)}{\int_0^{\infty} c(t)dt} \quad (1)$$

The mean residence time is then given by :

$$t_m = \int_0^{\infty} tf(t)dt = \frac{V_f}{Q} \quad (2)$$

Dimensionless time can be defined:

$$\theta = \frac{t}{t_m} \quad (3)$$

$$f(\theta) = t_m f(t) \quad (4)$$

The variance represents the axial dispersion:

$$\sigma_t^2 = \int_0^{\infty} (t - t_m)^2 f(t)dt \quad (5)$$

and,

$$\sigma_{\theta}^2 = \frac{\sigma_t^2}{t_m^2} \quad (6)$$

It can be related to the dispersion number, Peclet number, Pe .(Levenspiel et Smith,1957).

$$Pe = \frac{u_m L}{D} \quad (7)$$

where u_m : axial flow rate,
L: axial length,
D: eddy diffusivity.

$$\sigma_{\theta}^2 = \frac{2}{Pe^2} - \frac{2}{Pe^2}(1 - \exp(-Pe)) \quad (8)$$

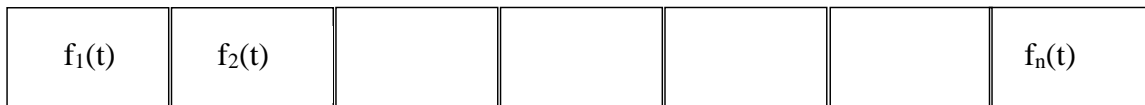
Superposition of RTD functions

Consider n statistically independent screw elements with the individual RTD functions $f_1(t)$, $f_2(t)$, ..., $f_n(t)$. This statistic independence requires perfect mixing or a uniform concentration at every boundary that connect two subsystems. Moreover each subsystem must be closed. So particles in the downstream subsystem do not communicate with adjacent ones. (Chen et al., 1995).

The overall RTD $f(t)$ is equal in the Laplace domain (Nauman and Buffham, 1983):

$$\bar{f}(s) = \bar{f}_1(s)\bar{f}_2(s)\dots\bar{f}_n(s) \quad (9)$$

In the time domain:



$$f(t) = \int_0^t f_1(\tau_1) \int_0^{t-\tau_1} f_2(\tau_2) \dots \times \int_0^{\tau_{n-3}-\tau_{n-2}} f_{n-1}(\tau_{n-1}) f_n(\tau_{n-2} - \tau_{n-1}) d\tau_{n-1} \times \dots d\tau_2 d\tau_1 \quad (10)$$

RTD Model

As a first approximation, the RTD in an individual turn of screw channel can be represented by the RTD model for a single screw extruder filled with a Newtonian melt, developed by Pinto and Tadmor [10], used by Wolf and White [11] and by Chen et al.[5].

The equations are based on parallel plates model and constant depth of the channel. The distribution function $f(t)$ is represented by:

$$f(t) = \frac{9v_b(1+\Theta) \sin\theta \times \cos\theta}{2L} \frac{a^3(a-1-(1+2a-3a^2)^{0.5})^3}{(6a^2-4a-1)(3a-1+(1+2a-3a^2))} \quad (13)$$

where $a=y/H$ ($a < 2/3$), y measures the distance from the screw root and H the channel depth,

θ represents the helix angle,

L is the axial length,

V_b is the barrel velocity,

V_z the down channel velocity component of the barrel,

The ratio of pressure to drag flow, Θ noted Θ , is defined by the equation 14 and is related to the flow rate through the relation 15:

$$Q = \frac{WHV_z}{2}(1+\Theta) \quad (14)$$

$$\Theta = -\frac{H}{6v_z} \frac{1}{\mu} \frac{\partial P}{\partial z} \quad (15)$$

where μ represents the viscosity.

The time is related to a by:

$$t = \frac{L}{3v_z(1+\Theta)} \frac{1}{\sin\theta \times \cos\theta} \frac{3a-1+3(1+2a-3a^2)^{0.5}}{a(1-a+(1+2a-3a^2)^{0.5})} \quad (16)$$

The mean residence time is equal to

$$t_m = \frac{2L}{v_z(1+\Theta)} \frac{1}{\sin\theta \times \cos\theta} \quad (17)$$

Experimental

The extruder is a Clextral BC21 fully intermeshing corotating twin screw extruder. The length of the barrel is 900 mm, the diameter 25 mm, the centerline 21 mm.

Figure 1 presents the screw profile used for studying the influence of operating conditions (Screw profile A) and the other for the convolution and deconvolution studies (Screw profile B). It also indicates the injection and detection locations.

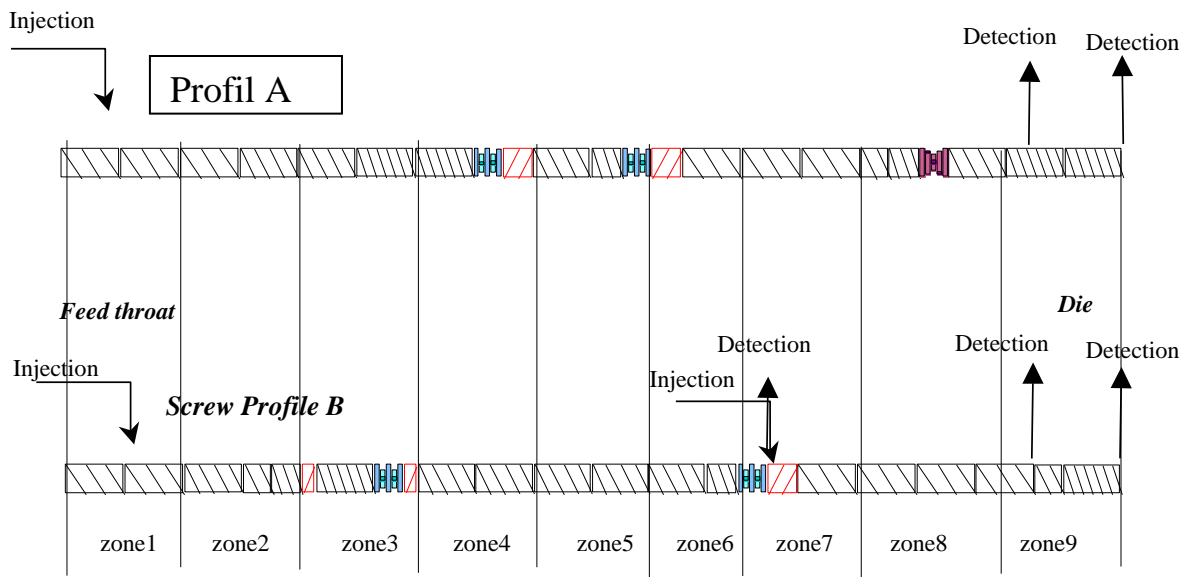


Figure 1. Screw profiles

Some explanations about the screw elements are given at the figure 2.

Profil B

Conveying element, type C2F

Pitch (mm)	16.66	25	33.33	25	33.33
Length (mm)	50	50	50	25	25

Reverse element, type C2F

Pitch (mm)	16.66	25
Length (mm)	50	50

Kneading block, type BLO2

Rotation		90°
Length (mm)	50	50
		45° left

Figure 2. Screw elements

A fluorescence monitoring device is used to measure in real time the RTD function. The fluorescent spectroscopy is well known to be very sensitive. Optical fiber probes, made in silica to endure hot temperatures, are capable to transmit optical excitation energy (UV light around 365nm) and to detect the fluorescence response (anthracene response around 400 nm).

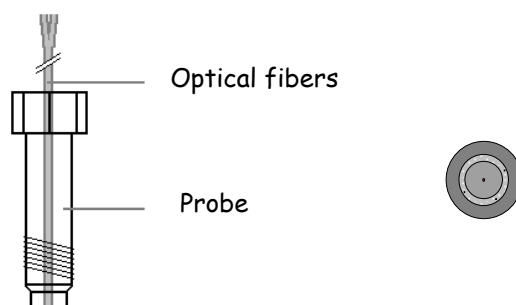


Figure 3. Optical fiber probes (length 1,5 m, diameter 6 mm)

Two fluorescent tracers have been used:

a microtracer: 9-(methylamino-methyl)-anthracene ; a batch is made with 1% wt. anthracene and polyethylene, and a macrotracer: anthracene bearing polyethylene. (Kadri, 1999) A batch is also made with polyethylene. This macrotracer ensures to have the same rheological behaviour as polyethylene.

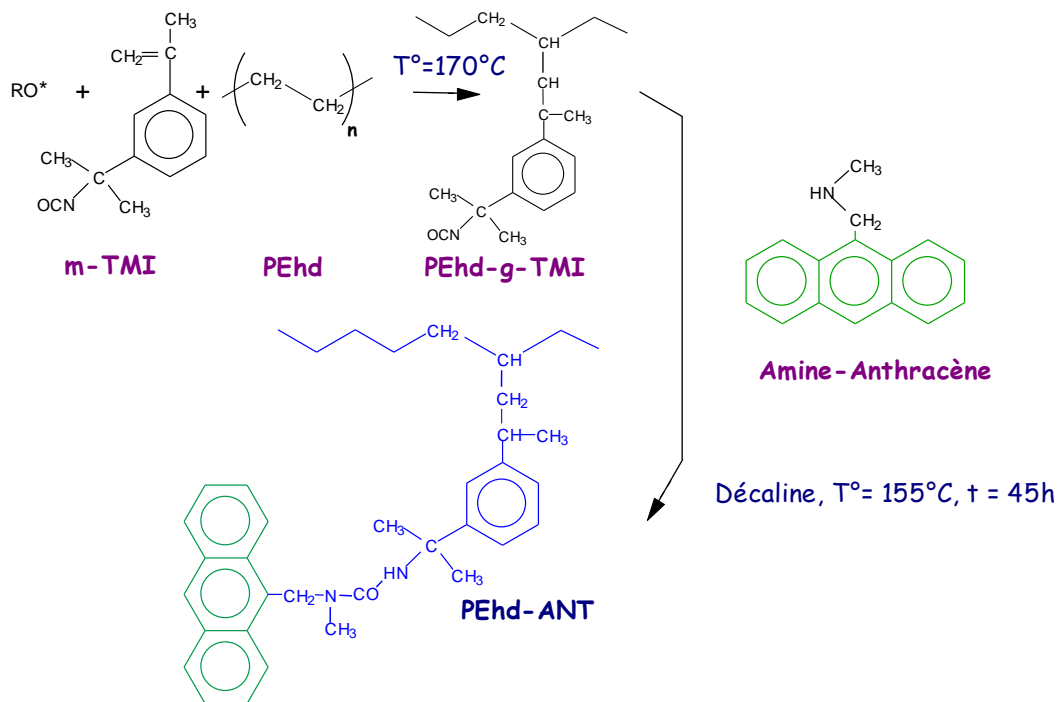


Figure 4. *Fluorescent macrotracer preparation*

Tracers are injected at different locations along the extruder. At the feed throat, pellets of tracer are injected as a pulse. In the melt zone, pellets are melt and injected thanks to an air pulse jet.

The detection system is shown on the figure 5.

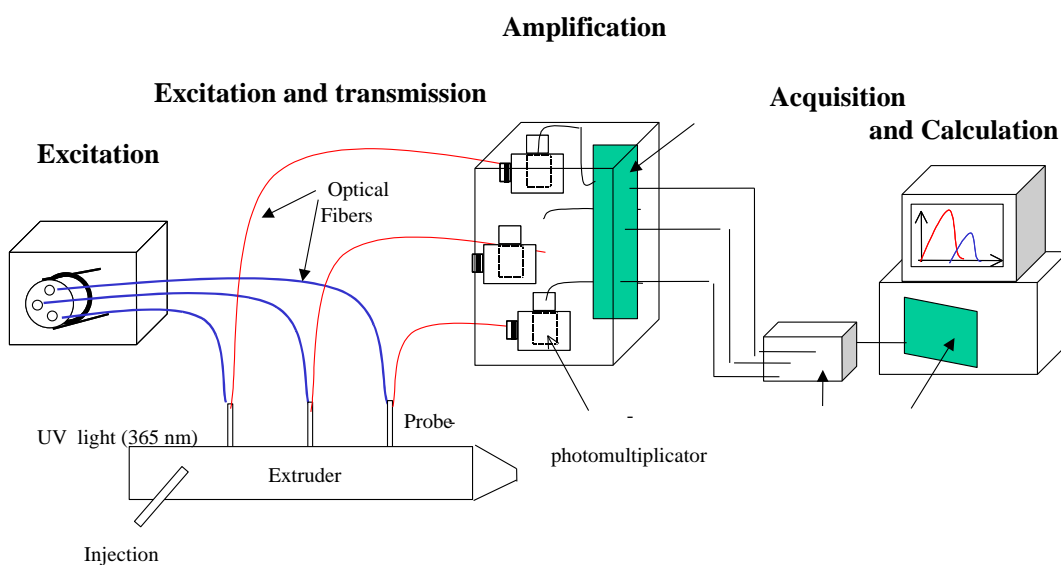


Figure 5. *RTD measurement system*

Results and discussion

Validation of the technique of detection

The screw profile used is shown figure 1 (Screw profile A).

Validation of the system

The reproducibility of the measurements has been checked.

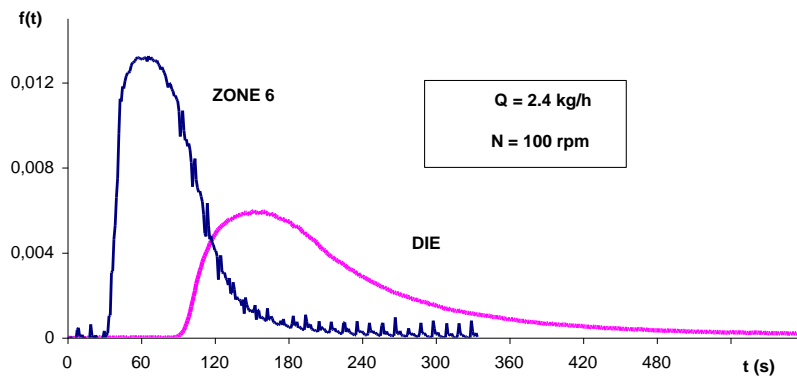


Figure 6. Local and overall RTD functions

As expected, the distribution is wider and the mean residence time is longer for the overall RTD detection.

Validation of the tracer

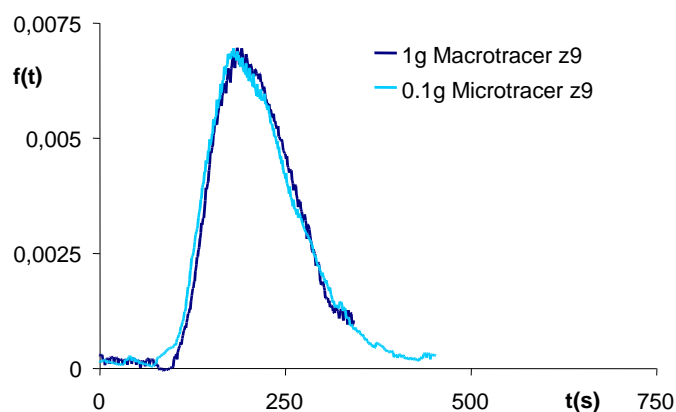


Figure 7. Equivalence of RTD functions for macrotracer and microtracer

The macrotracer gives the same signal as the microtracer. For the other experiments the microtracer will be used.

Linearity verification

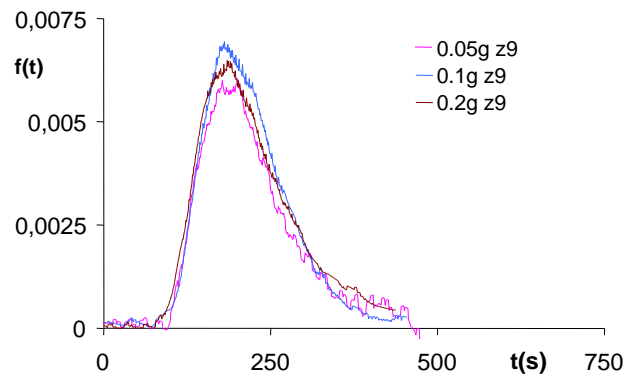


Figure 10. Influence of the quantity of tracer injected

After normation, signals are equivalent whatever the quantity of tracer injected. It proves that the signal is proportionnal to the concentration of tracer.

Influence of operating conditions

As expected, an increase in screw speed makes the mean residence and the dispersion time decrease. A throughput increase makes the mean residence time and the dispersion decrease.

Specific throughput

In reactive extrusion, the quality of a product is related to the quality of mixing. Specific throughput is an operating parameter for characterizing distributive mixing and is defined as the ratio of volumetric flow rate to screw speed, Q/N , (Bigio).

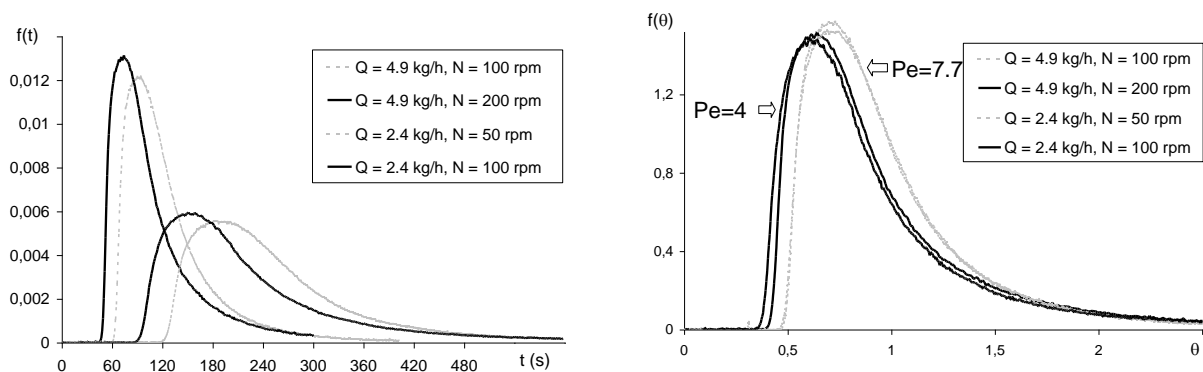


Figure 9. Influence of specific throughput at the die

The variance σ_{θ}^2 represents the distribution width and is correlated to the Peclet number. If Q/N is maintained constant, the same dispersion is obtained. It ensures the same quality of mixing.

Verification of the convolution theory

The convolution theory can be verified between independent elements. In our experiments, staggered elements included to the screw profile at the beginning of zone 7 (figure 1, Screw profile B) enable to obtain perfect mixing (almost in two dimensions).

In theory, f must be equal to the convolution result of f_1 and f_2 . Figure 12 shows the principle of the convolution.

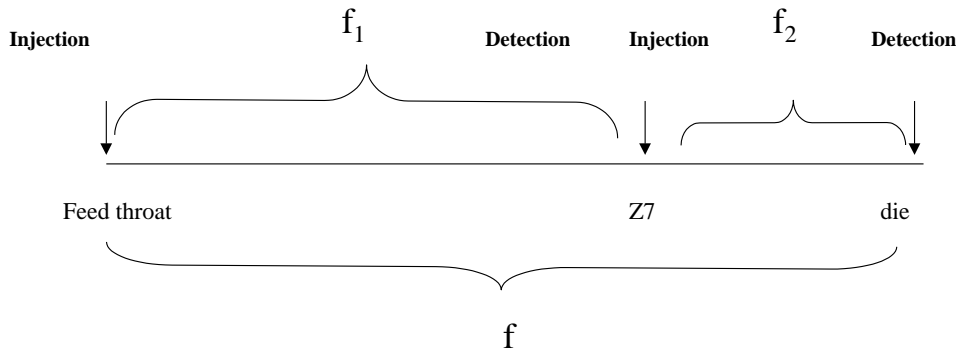


Figure 12. Convolution

The operating conditions are: $Q=20,7$ g/min and $N=200$ rpm. The tracer used is a masterbatch of polyethylene and microtracer (1% wt). The quantity injected is 0,1 g.

Experiment number	Injection location	Detection location
N1	Feed throat	Z7
N2	Z7	die
N3	Feed throat	die

Table 1. Operating conditions

The convolution of f_1 and f_2 has been numerically calculated and compared to the RTD function obtained in the experiment N3.

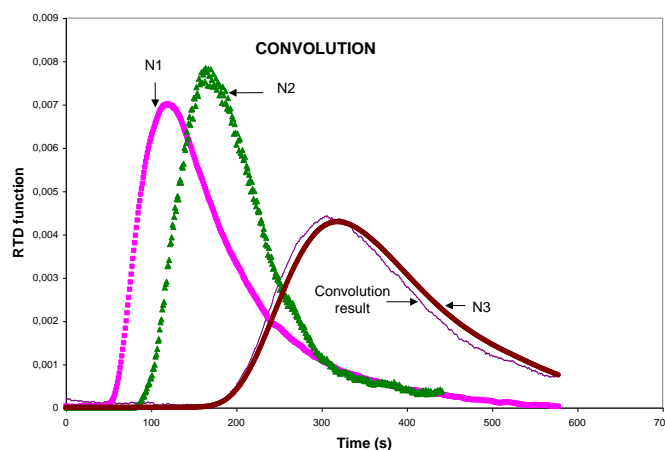


Figure 13. Convolution validation

The theory of convolution between two independent elements has been verified. We aim at using the theory of convolution and deconvolution to find a predictive model for RTD screw twin screw elements.

Examination of the predictive model

We propose to model a twin-screw zone composed of conveying screw elements.

The theory of convolution can be used between statistically independent elements. Convenient individual zones have to be chosen to model the screw elements (between zone 7 and zone 9).

The flow is supposed to be sufficiently randomized in the apex area. The RTD functions in any two adjacent half-turns of the screw channel (Chen et al , 1995.) are independent. So, a comparison between the multiple convolution of those individual elements and the overall RTD can be made. The number of elements has to be calculated to fit the overall signal.

Two models can be proposed depending on the degree of fill. The first one represents the flow behaviour as a plug flow. The second one considers the RTD of each individual element can be represented by the RTD model introduced by Pinto and Tadmor (1970) for a single screw extruder filled with a Newtonian melt.

Before introducing the models, the studied section is described.

The screw profile is shown at the figure 1.

The zone 7-zone 9 section that we investigate to model, is composed of 4 screw elements. The geometrical characteristics of each element are the following:

Length $L=5\text{cm}$,

Channel depth $H=0.5\text{ cm}$

Channel width $W=1\text{ cm}$

Diameter $D=25\text{ mm}$

Pitch $L_s=25\text{ mm}$

Helix distance $Z=6.27\text{ cm}$,

The calculated angle helix θ is equal to 17.7° ($\tan\theta=L_s/\pi D$)

The operating conditions are: $Q=20.7\text{ g/min}$ and $N=200\text{ rpm}$.

The HDPE density is equal to $d=0.952\text{ g/cm}^3$

The first model is applied supposing that the section zone 7- zone 9 is partially filled. The flow behaviour can be compared to a plug flow.

The experimental mean residence time obtained for this section is equal to 86.4 s .

The distance made by a particle for each half-turn would be $\frac{3L}{4} \frac{1}{2\sin\theta}$

The axial distance of 4 screw elements is $4L$.

So, if the rheological behaviour was the same as a plug flow the particle would reach the end after $2/3$ turns.

The screw speed equals $N= 200\text{ rpm}$.

The effective mean residence time should be 1.6 s , which is much shorter than the experimentally measured mean residence time (86.4 s).

Moreover, the experimental RTD distribution obtained for this section does not look like a Dirac as the curve N1 shows on the figure 13. A plug flow behaviour must be rejected. That screw section was probably not partially filled over its entire length. It would be composed of a partially filled zone followed by a fully filled one.

For the second model, the zone 7 - zone 9 part is supposed to be fully filled in the entire length and we consider the RTD of each individual element can be represented by the RTD model introduced by Pinto and Tadmor (1970) for a single screw extruder filled with a Newtonian melt.

The RTD model developed by Pinto and Tadmor allows to calculate the RTD distribution for each half-turn of screw channel.

In the operating conditions,

$$v_b = \pi DN = 0.26\text{m/s} .$$

$$v_z = v_b \times \cos\theta = 0.25\text{m/s} .$$

$Q=20.7$ g/min corresponds to a volumetric flow rate 0.3625 cm³/s.

$\Theta = 0.942$ which represents a difference of pressure vs. viscosity for the section z7-z9 of $37798 \times \mu$ Pa.

This result proves the existence of a fully filled length. This value will be determined in the future.

The mean residence time can be calculated for each half turn.

Z is 6.27 cm.

Therefore, the calculated t_m equals 8.65 s.

The experimental overall mean residence time is 86.4 s. It corresponds to about 10 independent elements.

In fact, 10.66 half turns effectively constitute the section zone 7-zone 9. Indeed 1 turn represents $3L/4$ so $4L$ represents 5.33 turns.

The appropriate individual elements may correspond to each half-turn of the screw elements.

The model has been verified with the mean residence time, it must now be extended to the residence time distribution.

The RTD function for each half turn modelled by the equations of Pinto and Tadmor (1970) is represented at the figure 14.

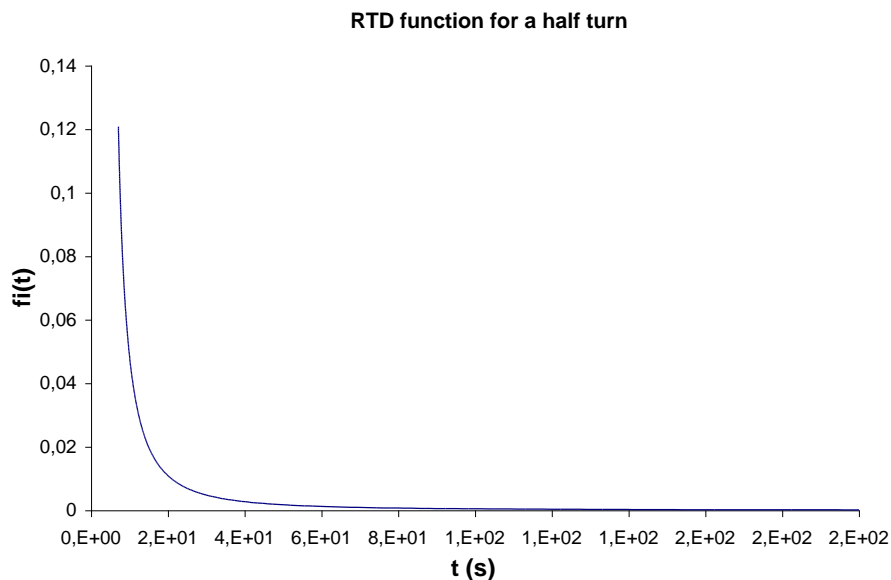


Figure 14. RTD function for a half turn

The first particle which will reach the following half turn with a delay equal to $Z/v_z = 0.25$ s.

The first step is to make the convolution of $f(t)$ with $f(t)$ delayed of 0.25 s. The result is convoluted with $f(t)$ delayed of 0.5 s compared to the first function and so on. We aim at approaching the experimental RTD and to find the number of individual half turns necessary to model the screw elements.

Conclusion

This paper deal with the determination of local RTD. It shows the validity of the fluorescence method. It validates the theory of convolution and uses it to model screw elements.

Some improvements have to be made to the model. The conditions of applications of the theory of convolution have to be defined.

The effective percent channel fill and the filled length have to be determined in the future. For the partially filled section, it will be assumed to have a plug flow behaviour and for the fully filled we can apply the model we used in this paper.

Thanks to the convolution theory, each section of an intermeshing twin screw extruder can be reached by a deconvolution method.

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