Visual Examination of the Effects of the Different Operating Conditions on the Residence Time Distribution in a Single-Screw Extruder with Transparent Barrel

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Abstract: In this study, the residence times of the polymeric materials were calculated via styropor grains as tracers under different operating conditions using a single-screw extruder with a transparent barrel as the first novel design in the literature and the performance values of the single-screw extruder system with a glass barrel were confirmed by the distribution results of the tracers. EVA was used as the polymeric material. In the studies, the motions of the tracers in different regions of the single-screw extruder were observed with naked eye and the movement from the regions towards the extruder exit was recorded by means of a camera. It was observed that the tracers proceeded in bulk for the solid conveying, the melt and the melt pumping zones in the extruder as the screw speed increased. Due to an increase in temperature, the low viscosity led to a wider dispersion of the tracers.

Introduction

The residence time distribution, RTD, is considered as one of the key parameter for characterizing the performance of an extruder. Since the shape of RTD functions depends on the combined effect of the flow patterns developed, the existing mixing mechanisms and also of heat transfer and reaction processes, RTD is often used to monitor and control important process attributes, such as consistency, extent of polymer degradation and degree of mixing [1]. The shear and temperature history of extruded product, conversion in reactive extrusion etc. are directly dependent on the RTD [2]. Hence, knowing and controlling RTD in industrial extruders are important to the quality of the output. For example, in the case of PVC, polymer chains exposed to high extrusion temperatures for prolonged periods of time are more likely to degrade to toxic products. In these cases, it is desirable to minimize the RTD in the extruder [3] as it is directly linked to contact time of reactants [4]. Also, the rheological properties of the polymer have a significant impact on fluid flow in an extruder [5, 6]. In addition, screws of good performance should not only have good plastication behavior, stable extrusion characteristics, and high output rate but also a good mixing capability [7].

There are many publications dealing with the RTD in an extruder in the literature. Ainsworth et al. [8] studied the effects of feed rate and screw speed on RTD of tarhana in a twin-screw extruder and found that increasing feed rate or screw speed, while keeping the other operating conditions constant, reduced the mean residence time (MRT) with the feed rate having a more pronounced effect than the screw speed and the flow in the extruder approached plug flow as the feed rate increased, whereas an increase in the screw speed resulted in the flow approaching mixed flow. De Ruyck [9] showed that the greatest influences on the MRT and RTD of wheat flour in a twin screw extruder were obtained by changing screw profile, screw speed and feed supply. Yeh et al. [10] modelled RTDs for single screw extrusion process and reported that increasing the feed rate caused the reduction in RT. Also high screw speed resulted in short RT, but large dispersion number. They showed that [11] the flow pattern in a single screw extruder can be obtained by regression without knowing the characteristics of the screw profile or the extruder for an extrusion cooking. To measure the RTD in real time, Hu et al. [12] constructed a fluorescence monitoring device in which the source of fluorescence emission was an anthracene-bearing substance that was injected to the flow stream as a pulse (tracer) in very small amounts and demonstrated that this device was accurate and reliable for on-line monitoring of the RTD in screw extruders. Iwe et al. [13] studied the influence of feed composition, screw rotation speed and die diameter on RTD of soy-sweet potato samples using congo red as a tracer in a single-screw extruder and found that the mean residence time depended significantly on the level of soy flour in the mixture as well as on the screw speed of the extruder and the flow of the mixtures was mainly plug flow. Apruzzese et al. [14] carried out in-line measurement of RTD in a co-rotating twin-screw extruder and showed that the rapid, simple in-line method accurately predicted the effects of temperature, feed and water rate as the three extrusion parameters on RT and mixing inside the extruder.

Seker [15] investigated RTD of starch extruded with sodium hydroxide and sodium trimetaphosphate in a single-screw extruder at 40% moisture content and showed that the increase in screw speed from 90 to 140 rpm reduced the MRT of the starch sample with a mixing element, but replacing the screw having one mixing element with a screw having two mixing elements increased MRT. The researcher recommended increasing the number of mixing elements at high screw speed for homogeneous treatment and reaction of the feed material in the extruder. A non-labor intensive, non-destructive method based on digital image processing was developed to measure RTD in a laboratory extrusion process by Kumar et al. [16] and it is shown that the increase in screw speed and temperature resulted in decrease in the MRT and an increase in degree of mixing. Waje et al. [17] studied RTD in a pilot-scale screw conveyor dryer (SCD) and revealed that the increase of screw speed resulted in a decrease in MRT and an increase in degree of mixing. Also they demonstrated that the flow in a SCD approaches plug flow as the feed rate was increased, whereas an increase in the screw speed resulted in a mixed flow.

Bi et al. [18] developed a convenient, inexpensive and simple digital image processing (DIP) method for measuring the RTD in a plasticating extruder and it was found that the repeatability and the linear relationship between the red color intensity and the concentration of the tracer proved the feasibility of the DIP method, so did the comparative experiment and in addition, the MRT was proportional to reciprocal values of the feed rate and the screw speed. Nikitine et al. [19] studied the RTD of Eudragit E100 polymer/supercritical CO_2 ($scCO_2$) through a single screw extruder which allowed injection of $scCO_2$ used as physical foaming agent and it was reported that high screw speed or high temperature gave short RT, but these parameters did not have the same effect on polymer flow.

Besides in the flow rate range studied, it was observed that $scCO_2$ had no significant influence on the RTD curves. Nwabueze et al. [20] extruded African breadfruit mixtures to assess RTD of them in a single screw extruder and it was found that extrudate temperature was linearly and quadratically influenced by feed composition, feed moisture and screw speed depending on the process conditions and also an increase in screw speed (100-180 rpm) and decrease in feed moisture (27-15%) increased thermal and shear energies, and hence, extrudate temperature.

Experimental Methods

Equipment and experimental set-up: Single-screw extruder system containing a transparent barrel used in this study is shown in Fig. 1. The transparent glass readily enables observation of the flow characteristic of the flowing material inside the barrel and facilitates the temperature measurement via an infrared thermometer. The steel screw in the transparent glass barrel is directly connected to the gear box of the motor. The control of the motor is governed by means of a driver. Transparent glass barrel is separated into four distinct temperature zones. Each zone is isolated by teflon o-ring. Consequently, the temperature of each zone is individually controlled. The hot oil system is used to set the barrel temperature to the desired temperature.

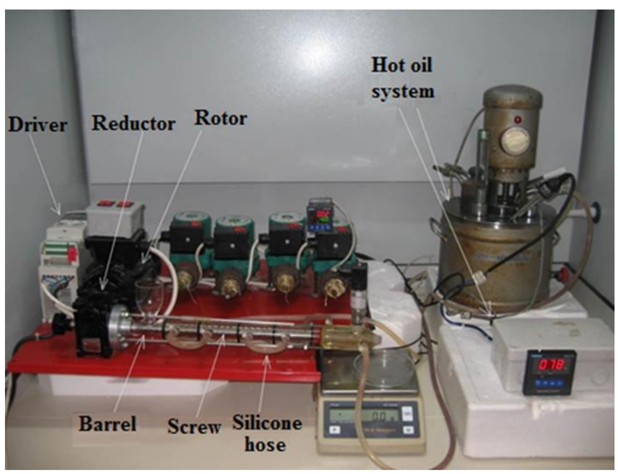

Fig. 1 Extruder system with transparent barrel.

Barrel: The extruder barrel in this study is composed of two nested-glass tubes. One is inner glass barrel enclosing the screw and the other is the outer glass jacket which retains the hot-oil as shown in Fig. 2. The area between the inner and the outer barrel comprises four zones that are not only separated from each other by teflon separator but also with the inlet and outlet sections for recirculation of the heat transfer oil used for heating.

Fig. 2 Heating zones on the barrel.

Screw: Each one of the three different screws used in this study has different feeding and metering zone lengths and a unique design. The screws have such a length that they embody the feeding, the compressive and the melt conveying zones. The melting zone lengths of all the screws in Fig. 3 are the same. The feeding and the metering zone length for the first, the second and the third screw all of which are manufactured by Mikrosan Corporation are 15D and 7D, 13D and 9D, 11D and 11D, respectively. In our study, L/D ratio is 29 and compression ratio, i.e. the flight depth in the feeding zone/the flight depth in the melt conveying, is 2.5/1.5.

Fig. 3 The screws used in this study (the colored zones indicate the melting zone).

Materials: In the experiments, Elvax 40W (ethylene-vinyl acetate) copolymer provided by Dupont-Belgium was used. Some physical and chemical properties of Elvax 40W are given in Table 1.

Table 1 Some physico-chemical properties of Elvax 40W.

Property	**Elvax 40W (DuPont)**
VA content (weight percent)	39 – 42

Melt index (g/10 minutes)	48 – 66
Melting temperature (◦C)	~ = 50
Crystallinity (%)	<10
Tensile strength at break (MPa)	4.8 – 6.2
Elongation at break (%)	1000 – 1300
Hardness (Shore A)	40
Density (g/cm^3)	0.965

EPS (expanded polystyrene) provided by EastChem Corporation (Izmir, Turkey) was used as tracer in the experiments and its some physical properties are given in Table 2.

Table 2 Some physical properties of EPS used as tracer.

Properties	**Sytrafor (EastChem)**
	Eurocell® 200F
Size range of grains (mm)	0.9 – 1.25
Sieve analysis (mm)	0.9 – 1.4 (min. 96 %)
Bulk density (kg/m^3)	≈ 615 kg/m^3

Residence Time Distribution (RTD): In this study, residence time distributions in the single-screw extruder with glass barrel were found by using pulse method. The bulk material (EVA 40W) is fed into the extruder from the feed hopper until the extruder system is reached steady state which implies that the flow rate, pressure and temperature are not changing. 0.250 g of the tracer was instantly fed into the system following the steady state. The mixture of the melted bulk material and the tracers was collected every 10 seconds. The collected samples were transformed into the film form (Fig. 4). This treatment was carried out for the temperature values of 55, 65, 75 °C and at the screw speeds of 30, 50 and 70 rpm. The three different screws and each experiment were repeated at least three times. Residence time distribution E(t) in Eq. 1 and the mean residence time τ in Eq. 2 were calculated using the obtained data. The mathematical relationships for each one of these terms are as follows:

Residence time distribution (E(t)):

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

Mean residence time (τ):

$$\tau = \int_0^{\infty} tE(t)dt \tag{2}$$

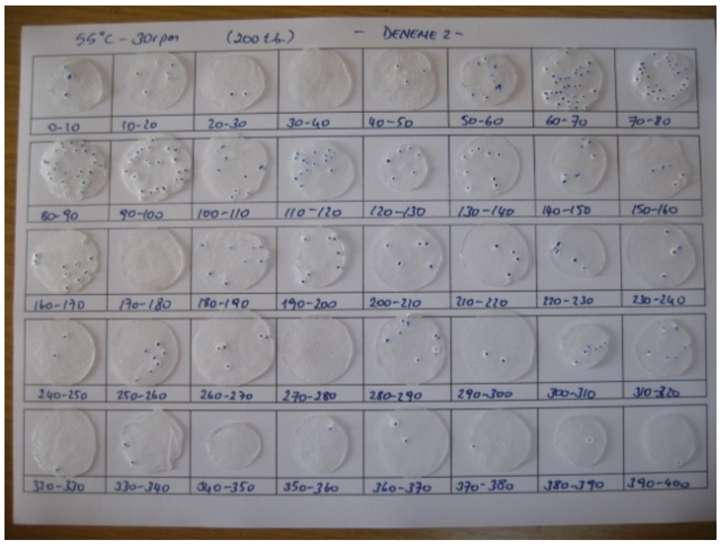

Fig. 4 The films obtained by hot-pressing bulk material-tracer mixture to determine the RTD.

Results and Discussion: In the following sections, the effects of screw speed and temperature on the extruder system are demonstrated.

The effect of screw speed on RTD: The residence time distributions based on the different screw speeds at 55, 65 and 75 °C are shown in Figs. 5, 6 and 7, respectively. From Fig. 5, it is reported that the RTDs decreased as the screw speeds for all the screw geometries increased at 55 °C. Also, the MRT decreases since the screw speed increases at the same temperature as in Fig. 8(a). The RTDs of screws 1 and 2 are similar to each other at 30 rpm and 55 °C, but there is little difference between the three screws at high screw speeds, especially at 50 and 70 rpm.

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As seen from Fig. 6, a narrower RTD is obtained compared to that in 55 °C as the screw speed increases at 65 °C, leading to a decrease in MRT. It is observed from Fig. 8(b) that as the screw speed increases at 65 °C, the effect of all the screw geometries on RTD diminishes, particularly at 70 rpm.

As the screw speed increases from 30 to 70 rpm for all the screw geometries, the RTDs, shown in Fig. 7, becomes narrower, consequently causing the MRTs to decrease as seen in Fig. 8(c). It is observed from Fig. 8(c) that, the screw geometries have a slight effect on RTDs obtained at 30 and 70 rpm for 75 °C. However, the RTDs at this temperature are significantly different for 50 rpm. The widest RTD were obtained using screw 1. It can be inferred from Fig. 8 that the narrowest RTD was obtained using screw 3 at 50 rpm for all the temperatures. The reason for that is the solid conveying length of screw 3 is smaller than the other screw geometries.

The temporal dispersion of the tracer inside the solid conveying, the melting and the metering zone of the glass-barrel extruder is videotaped as shown in Fig. 9. The effect of the lengths of the three different regions in the extruder on mixing was examined. An increase in the solid conveying zone length leads to bulk flow of the tracer such that the axial mixing decreases. The lengths of the melting zones of all the screws are the same. However starting from the entrance to the melting zone, the dispersion of the tracer increases rapidly for each screw geometry. The complete melting of the bulk material in the metering zone occurs. Therefore the viscosity of the bulk material decreases depending on the temperature and the friction and the molten pool takes place such that the tracers can move independently from each other. As a result of this movement, the distance between each tracer increases and accordingly, the axial mixing increases.

Increasing screw speed leads to a better axial mixing; on the other hand, the time required for mixing decreases. This also negatively affects obtaining a good mixing. The MRTs obtained at 70 rpm for all the temperatures in this study is lower compared with those at 30 and 50 rpm. Although the degree of the dispersion is high at high screw speeds, a screw speed of 70 rpm may not be the best operation condition.

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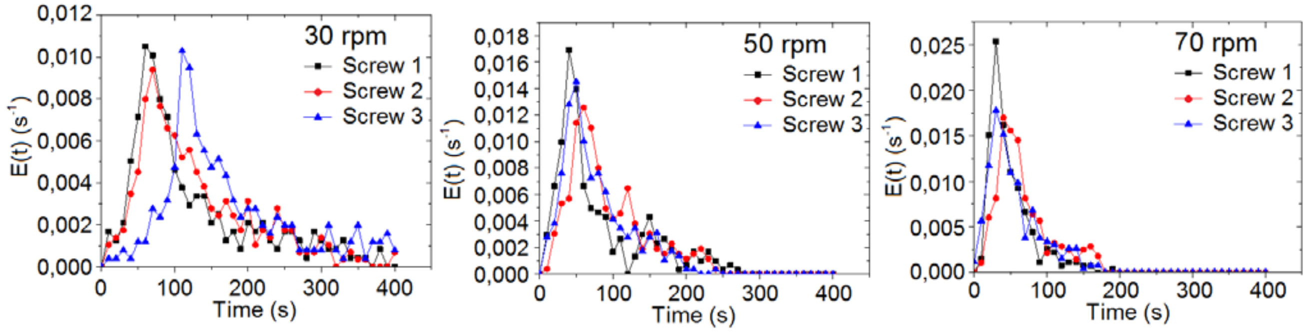

Fig. 5 The effect of the different screw geometries on RTD at 30, 50 and 70 rpm for 55 °C.

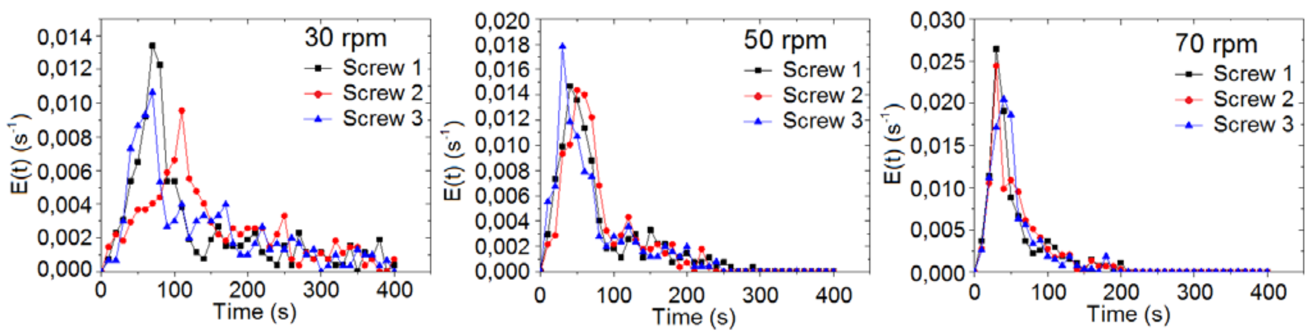

Fig. 6 The effect of the different screw geometries on RTD at 30, 50 and 70 rpm for 65 °C.

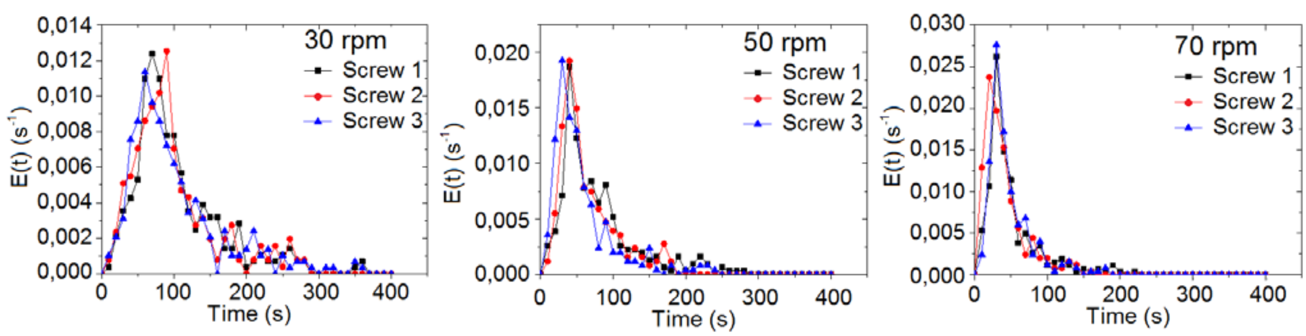

Fig. 7 The effect of the different screw geometries on RTD at 30, 50 and 70 rpm for 75 °C.

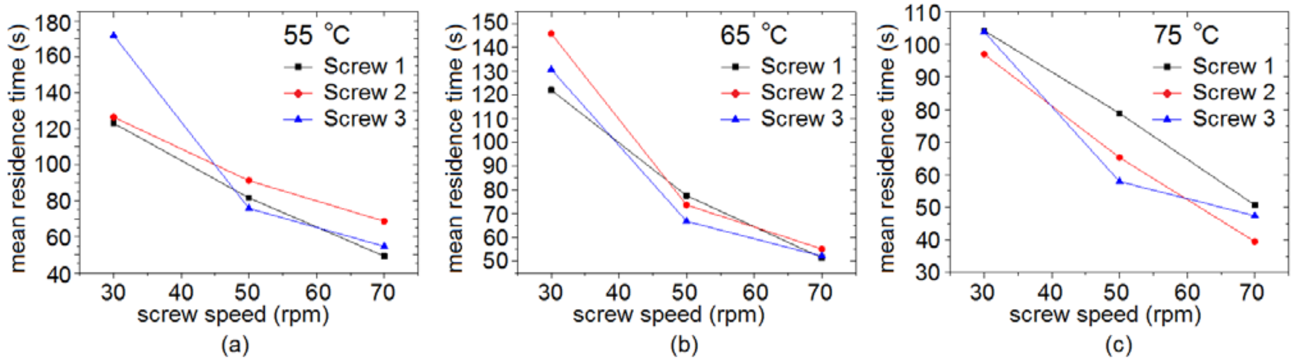

Fig. 8 The effect of the different screw designs and the different screw speeds on MRT at (a) 55, (b) 65 and (c) 75 °C.

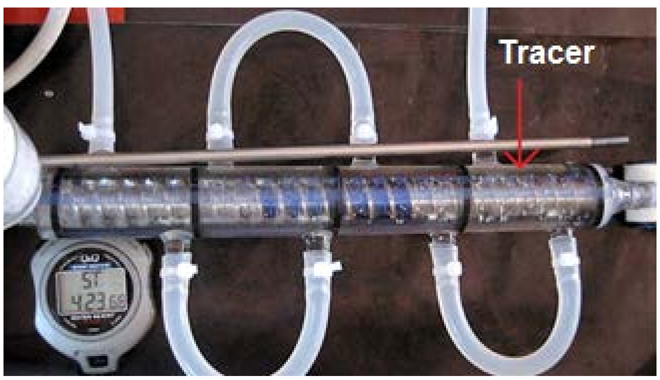

Fig. 9 The temporal dispersion of the tracer in the different zones of the single-screw extruder with the glass barrel

Conclusions: Single-screw extrusion process in this study was investigated. A glass-barrel extruder produced and designed specifically was used to clearly observe the material flow in the solid conveying, the melting and the metering zones. To date, this extruder is not available in the literature and it is established that a net flow of the material inside the extruder was seen apparently and it behaves as a melt in a major part of the barrel. It is determined that the material floats on the molten shortly after some degrees of the melting are taken place by compression, i.e., the first melting seen in the solid conveying zone. Thus solid profile X/W, the flow rate in the solid bed V_{sz}, the positions of the upper melt, the melt pool and the occurrence of the solid bed breaking was monitored sensitively. The numerous dynamic properties of extrusion such as non-plug solid conveying, the breaking of the solid bed and the melting of the breaking solid granules were tracked in-situ constantly behind the glass-barrel extruder.

The output increases in direct proportion to the screw speed. Increasing the screw speed causes a decrease in MRT. The reduction in MRT is more pronounced using screw 2 and 3 because of an increase in screw speed. Among the three screw types, the shortest mean residence time is reached using screw 3 at 50 rpm for all the temperatures. The RT in the solid conveying zone of the extruder decreases with increasing screw speed.

The RTD becomes narrower as the temperature increases from 55 to 75 °C, but at the same time the axial mixing increases with the increasing of temperature. There is a considerable temperature effect on the RTDs obtained using screws 2 and 3 because the length of the metering section, where the polymer is completely in the molten state, of screws 2 and 3 is bigger than that of screw 1. Increasing temperature from 55 to 75 °C improves the axial mixing at 70 rpm for screws 1 and 2. The blend homogeneity increases as temperature increases for all the relevant screws.

With this study, the dispersion of the tracers in the completely transparent glass barrel can be observed and the flow regime can be determined. Also, it will give insight into the understandings of flow characteristics of polymeric materials.

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