Residence Time Distribution and Barrel Fill in Pet Food Twin-Screw Extrusion Cooking

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ABSTRACT

The residence time distribution and barrel fill of pet food in a twin-screw extruder was determined under conditions of a constant ratio of feed rate to screw speed. Specific feeding load was held constant at 0.16 kg/hr/rpm while feed rate ranges were 24–56 kg/hr and screw speed ranges were 150–350 rpm. The residence time rapidly decreased as feed rate and screw speed increased. The spread of the residence time distribution (RTD) was smaller at higher feed rates and screw speed, however analysis of the normalized RTD indicated greater mixing. The barrel fill was constant at ≈50% throughout the range of experimental conditions.

Extruders are used extensively in the food industry to create products with a wide range of functional characteristics. The self-wiping twin screws in a twin-screw extruder permit better control of the residence time distribution (RTD) than do single screws because there is no continuous channel for uninterrupted pressure flow and no stagnant zones in the lee side of the flights. The RTD is a measure of the length of time process material spends in the extruder, and the RTD data are most useful in diagnosing axial mixing phenomena in twin-screw extruders, providing the basis for scale-up and providing leads to improvement in equipment design (Todd 1975, Choudhury and Gautam 1998). The RTD also gives information on the probable residence time of the particles, the degree of uniformity of the shearing on the particles, and the temperature-time combinations, factors important for preparing a product of good quality in food extrusion (De Ruyck 1997).

Residence time is considered a system parameter that links process variables (such as screw speed and moisture content) and product parameters (such as texture and taste). Residence time in food extrusion determines the extent of chemical reactions and, ultimately, the quality of food extrudates (Gogoi and Yam 1994). Several researchers have studied the effects of process variables such as screw speed, throughput, and screw configuration on residence time and RTD in twin-screw extrusion cooking. Olkku et al (1980) reported broadening of RTD occurs over mixing elements such as reverse screw elements, while Mosso et al (1982) showed that an increase in screw speed markedly reduced the minimum residence time with no change in the spread of RTD. However, increase in throughput was accompanied by a decrease in residence time and a marked decrease in the spread of RTD. Choudhury and Gautam (1998) found that an increase in feed flow rate resulted in higher and narrower peaks for RTD compared with the low feed flow rate.

The objective of this study was to determine relative residence time between varying conditions of feed rate and screw speed when the ratio of feed rate to screw speed is constant. The barrel fill under these conditions was determined to evaluate the suggestion by Meuser and Wiedmann (1989) that barrel fill is approximately constant if the ratio of screw speed to feed rate is maintained.

MATERIALS AND METHODS

Experimental Plan and Statistical Analysis

The experiment was a single-factor randomized complete block design with five levels for the single factor and two replicates. The feed rate was confounded with screw speed to maintain a specific feeding load at 0.16 kg/hr/rpm. Extruder responses and product attributes were subjected to analysis of variance and Fisher's mean separation analysis using PROC ANOVA (SAS Institute, Cary, NC).

Extrusion

A corotating and intermeshing twin-screw extruder (model ZSK 30, Krupp, Werner, and Pfleiderer, Ramsey, NJ) was used. The temperature profile was maintained at 40, 90, 120, 120, and 140°C for zones 1, 2, 3, 4, and 5, respectively. The screw profile is given in Table I. A single-hole die located in front of the right-hand screw (facing front of extruder) with a 5-mm diameter opening and an 11-mm land length was used. Feed rate was controlled by a loss-in-weight feeder. The feed system consisted of a controller with a feeder on a counterbalance scale (Schenck Accurate model 8000, Whitewater, WI). The raw feed material was pet food formula donated by the Ralston Purina Co. (St. Louis, MO).

Specific Volume

The specific volume (SV) was determined by the rapeseed displacement method. The volume of a canister was determined by weighing the canister empty first and again filled with water. The canister was filled with rapeseed and weighed, and the weight was used to calculate the bulk density of the rapeseed. Approximately 25.0 g of extrudate was put in the empty canister and weighed. The free volume of the canister was filled with rapeseed and weighed (canister + extrudate + rapeseed). The procedure was repeated six times. The SV was determined as:

SV = (canister volume – rapeseed volume)/weight of extrudate

Rapeseed volume = rapeseed weight/rapeseed bulk density

Extrudate Diameter and Die Swell

The extrudate diameter was determined by measuring the average diameter of the extruded strands with a caliper. Ten strands were measured and averaged for each sample. Die swell, a measure of the amount of expansion due to elastic effects, was determined according to the method described by Faller et al (1995):

$$\text{Die swell} = [(R_2/R_0)/(L_2/L_0)]^{1/3}$$

$$L_0 = \text{PPW}/\pi R_0^2\rho$$

where R_0 and R_2 = the radius of the die and the extrudate, respectively; L_0 and L_2 = the theoretical unexpanded extrudate length and the actual expanded extrudate length; PPW = per piece weight of the extrudate, and ρ = the density of the extrudate in the unexpanded state.

Moisture Content

The moisture content (mc) of the meal was determined by weighing ≈1.000 g of sample in an aluminum foil cup, heating the sample for 4 hr at 120°C, and cooling the sample in a desiccator. The loss in weight was taken to be the total moisture in the meal. During extrusion, the water feed rate was adjusted to bring the

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TABLE I
Extruder Screw Configuration

Zone	Screw Element: Flight Angle Type^a	No. of Screw Elements	Length of Screw Element (mm)
I (Feed)	20°: FTLS	1	14
	42°: FTLS undercut	2	42
II	42°: FTLS undercut-normal	1	21
	42°: FTLS	3	42
III	28°: FTLS	14	28
IV	20°: FTLS	2	20
	45°: FP	2	20
	20°: FTLS	2	20
	45°: FP	2	28
V	20°: FTLS	2	20
	45°: FP	1	20
	45°: FP	1	42
	90°: NP	1	28
	20°: FTLS	2	20
	45°: FP	1	28
	90°: NP	1	28
	45°: RP	1	14
	20°: FTLS	4	20
	Spacer	1	7
	20°: FTLS	1	10

[a] FTLS = forwarding twin lead screw; FP = forwarding paddle; NP = neutral paddle; RP = reversing paddle.

total moisture content of the feed to the predetermined level within the extruder (25.0% wb).

Residence Time Distribution

The residence time was determined by the impulse method using a colored plug added to the feed port. Feed material was mixed with red food coloring in the ratio of 5 g of meal to 2 g of dye and added in ratio to the feed rate for each condition at 0.15 g of dyed feed per kilogram of extruder feed material per hour. The samples were collected for 100 sec at 5-sec intervals. Before color measurement, the samples were dried and ground with a blender for 1 min. A colorimeter (Labscan 6000 0°/45° spectrocolorimeter Hunter Associates Laboratory, Reston, VA) was used to determine the *a* values of the ground samples, which were used to measure the red color concentration, C, which in turn was used for determining the mean residence time ($\bar{t}$), and the residence time distribution (RTD) spread (measured by the standard deviation, σ), adjusting for the baseline redness of each sample. Values for $E(t)$, mean residence time, and σ were determined according to:

$$\bar{t} = \sum_0^t tC\Delta t \,/\, \sum_0^t C\Delta t$$

$$E(t) = C \,/\, \sum_0^t C\Delta t$$

$$\sigma = \sqrt{\sum_0^t (t - \bar{t})^2 C\Delta t \,/\, \sum_0^t C\Delta t}$$

Normalized Residence Time Distribution

The RTD is normalized to the average residence time by substitution of $\theta = t/\bar{t}$ (Altomare and Ghossi 1986). Therefore:

$$E(\theta) = \bar{t}E(t)$$

Barrel Fill

The volume of the barrel occupied by product was determined from the volumetric flow rate of the material, $\dot{V}$, the free volume of the empty barrel, V_{barrel}, and the mean residence time as:

$$\text{Barrel fill}\,(\%) = 100\dot{V}\bar{t} \,/\, V_{\text{barrel}}$$

The free volume of a barrel containing only the screw is 447 cm^3/m of barrel length with a total length of 1.2 m; the density of the pet food inside the extruder was assumed to be 1.33 g/cm^3.

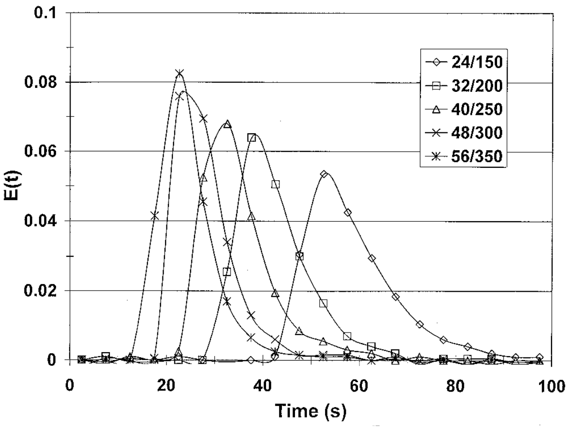

Fig. 1. Residence time distribution for five levels of feed rate (kg/hr) confounded with screw speed (rpm).

RESULTS AND DISCUSSION

The mean residence time decreased with an increase in feed rate confounded with screw speed (Fig. 1). These observations are consistent with those of other researchers (Altomare and Ghossi 1986, Gogoi and Yam 1994, De Ruyck 1997). Figure 1 shows higher and narrower peaks as the feed rate and screw speed increase, with the highest and narrowest peak being at a feed rate of 56 kg/hr and screw speed of 350 rpm. Choudhury and Gautam (1998), using an online measurement of residence time distribution in a food extruder, observed narrower and higher RTD peaks with high feed flow rates of 12 kg/hr compared with lower ones of 8 kg/hr. These workers also observed a large tail with low feed flow rates, an observation we made in our current work.

Normalizing the RTD plots allows a comparison of mixing patterns between the different conditions (Fig. 2). The trend from low to high screw speed and feed rate clearly indicates a broadening of the RTD$^{\text{norm}}$ at the high screw speed and feed rate condition. Also, the broadening occurs on the front side of the RTD$^{\text{norm}}$, with the tail being identical for all conditions. The broader RTD$^{\text{norm}}$ at the higher screw speed and feed rate indicates greater mixing. At this condition, a greater amount of material is being forced through the same size die and, therefore, greater rejection and backflow might be expected.

The system response and product attributes evaluated in this work are shown in Table II. The specific mechanical energy (SME), motor torque (MT), die pressure (DP), and product temperature (PT) remained fairly constant over the experimental conditions, with SME and MT increasing slightly as feed rate confounded with screw speed increased. An increase in mass flow independent of other parameters leads to a reduction in SME and an increase in DP (Meuser and Wiedmann 1989), while MT decreases with an increase in screw speed (Altomare and Ghossi 1986). The SME and MT mirror each other in the current study because feed rate and screw speed are confounded. Normally, an increase in temperature would be expected with increase in screw speed (shear rate), but an increased feed rate and lower residence time apparently prevents this. Indeed, SME only slightly increases.

The product attributes, die swell (DS), specific volume (SV), and extrudate diameter (D) remained essentially constant for all the different samples analyzed. In addition, barrel fill remained constant at ≈50% throughout the range, supporting the suggestion by Mueser and Weidman (1989). This suggests that the extent of cooking along the barrel length remains nearly constant as feed rate and screw speed are changed simultaneously. However, differences in product attributes other than those measured are suspected, as witnessed by the die pressure. Normally, a doubling in feed rate would be expected to nearly double die pressure, yet no significant pressure increase was observed between the lowest feed rate and the

TABLE II

Extrusion Response Parameters, Product Attributes, and Residence Time Distribution (RTD) Summary[a]

Sample (FR/SS)	SME	MT	DP	PT	DS	D	SV	BF	MRT	σ
24/150	256c[b]	51.1c	1,710	135.6	0.922	6.96	2.83	54.7	58.5a	10.3a
32/200	275ab	55.3ab	1,840	135.4	0.962	7.36	2.82	52.7	42.3b	7.7b
40/250	270a–c	54.0a–c	1,980	136.9	0.970	7.40	2.79	54.2	34.8c	7.6b
48/300	264bc	52.8bc	1,840	139.7	0.929	6.86	2.76	52.5	28.1d	6.7bc
56/350	280a	56.8a	1,860	139.5	0.945	6.94	2.78	53.0	24.3e	5.9c

[a] FR = feed rate (kg/hr); SS = screw speed (rpm); SME = specific mechanical energy (kJ/kg); MT = motor torque (%); DP = die pressure (kPa); PT = product temperature (°C); DS = die swell; D = diameter of extrudate (mm); SV = specific volume (cm^3/g); BF = barrel fill (%); MRT = mean residence time (sec); σ = SD of RTD (sec).

[b] Values followed by the same letter in the same column are not significantly different ($P < 0.05$). Values with no letters have no significant difference.

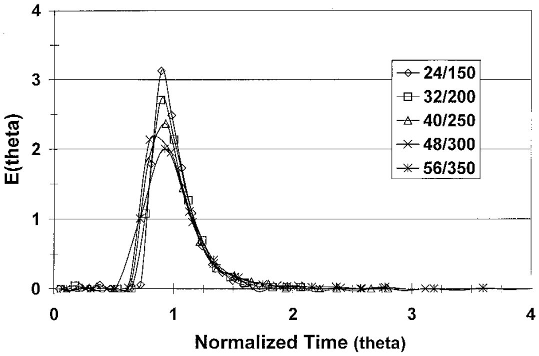

Fig. 2. Residence time distribution normalized to the average residence time for five levels of feed rate (kg/hr) confounded with screw speed (rpm).

highest, which represents a 2.33-fold increase in feed rate. Clearly, the viscosity of the melt is reduced at the higher screw speed and feed rate conditions. PT, which can influence DP because of its influence on viscosity, was fairly constant with a slight, non-significant increase. A similar result was seen by Mahungu et al (1998) with extrusion of cornmeal and soy protein blends where an increase in screw speed confounded with feed rate led to a reduction in die pressure with only a slight increase in product temperature. The more aggressive mixing and shearing environment at the higher screw speeds as shown by the RTD^{norm} plot (Fig. 2) is probably the main factor, with greater backflow resulting in more shear exposure. The increase in SME should contribute to this as well through mechanical rupture of molecular bonds and reduction in molecular weight. However, the product attributes appear to be more stable than if feed rate or screw speed are altered independently.

The consistency of the barrel fill between conditions while maintaining SFL suggests that using feed rate confounded with screw speed as an experimental design parameter can control the relative residence time (RRT) between conditions, which would be important for time at temperature-sensitive products such as when vitamin content or microorganism inactivation are critical. RRT can be predicted even if barrel fill is not known by taking the ratio of the actual feed rate to the slowest feed rate. In the present case, the predicted relative residence time between the highest and lowest feed rates would be (24 kg/hr)/(56 kg/hr) or that the highest feed rate would be in residence 43% as long as at the lowest feed rate. This compares with the 42% ratio found experimentally (Table II).

Also, these results tend to downplay the role of screw speed. Changing screw speed independent of feed rate leads to significant responses in product attributes and is a primary mechanism for extrusion control (Hauck and Huber 1989). This fact has been attributed to an increase in shear rate at the higher screw speed (Colonna et al 1989), but the increase in shear rate may not be as critical as it appears on the surface. The present results suggest that increasing screw speed alone will lower barrel fill, push cooking transformations toward the die, and thus produce the needed conversion over a shorter barrel length. Also, using a confounded design approach can allow evaluation of barrel fill as an independent parameter. It also allows a broader range of flow conditions because increasing screw speed independent of feed rate can produce unstable extruder responses when barrel fill is too low (Fichtali and van de Voort 1989).

CONCLUSIONS

This work has shown that when the ratio of feed rate to screw speed is maintained at a constant value, it is possible to simultaneously study the effect of feed rate and screw speed on the residence time distribution. The results also suggest that with a constant ratio of feed rate to screw speed, the barrel fill and, hence, the total mechanical energy input, remains almost constant. The other conclusion that can be drawn from this work is that, for a twin-screw extruder, it is possible to vary the extrusion conditions but still produce extrusion products with similar product attributes if the feed rate to screw speed ratio is maintained at a constant level. However, we must note that this work was with dry expanded pet food using a corotating twin-screw extruder; verification of these principles should be repeated for other types of food and extruders.

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