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米穀擠壓加工－螺絲元件組合、進料速率及螺軸轉速對滯留時間分佈F曲線之影響

Extrusion Cooking of Rice Flour – Effects of Screw Profile, Feed Rate, and Screw Speed on the RTD F Curves

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摘 要

比色法被用來測定米穀粉在雙軸擠壓機內之滯留時間分佈情形。本研究之加工變數爲：螺絲元件組合，進料速率及螺軸轉速。3×3×3之複因子設計用來研究加工變數對滯留時間分佈F曲線之影響。

研究結果顯示本實驗之加工變數對滯留時間分佈F曲線有顯著的影響。影響F曲線之最大加工變數是進料速率，其次是螺絲元件組合；螺軸轉速則是影響F曲線最小之加工變數。

關鍵詞：比色法，滯留時間分佈，雙軸擠壓機

ABSTRACT

A colorimetric method was used to study the residence time distribution (RTD) in an APV Baker MPF50/25 twin-screw extruder using rice flour as the feed material. The process variables were screw profile, feed rate, and screw speed. A 3 × 3 × 3 factorial experiment was designed to study the effects of process variables on RTD F curves.

The effects of process variables on the residence time distribution F curve were significant. The most important factor affecting the RTD F curve was feed rate. Screw profile was the second important factor and screw speed was the least important factor affecting the RTD F curves in this research.

Keywords: Colorimetric method, Residence time distribution, Twin-screw extruder

INTRODUCTION

Many food or feed products such as breakfast cereals, snacks, pet foods and animal feedstuffs are produced by extrusion cooking technology (Harper, 1981; Linko et al., 1981). Modern extruders are high temperature short time (HTST) units and have the ability to continuously mix, knead, shear, cook, form and puff the extrudates (Harper, 1981). Twin-screw extruders have better mixing, more uniform temperature distribution, better control of residence time, more positive displacement action, and operating at very low moisture than single-screw extruders (Harper, 1981; Lin and Armstrong, 1988). In recent years, twin-screw extruders have been used increasingly to process products in many industries, such as the plastic, food, rubber, metal, carbon and ceramic industries (Fellows, 1988; Harper, 1981; Mercier et al., 1989; Valentas et al., 1991).

The most important factors affecting the extrusion systems are the operating conditions of the extruder and the rheological properties of the food (Fellows, 1988). The residence time distribution (RTD) of the feed material in an extruder is one of the most important parameters characterizing mixing and chemical kinetics that occur in extruders. It is also a useful tool in determining the optimal operation conditions for blending, dispersing, and polymerization applications (Bruin et al., 1978; Lin and Armstrong, 1988). Todd (1975a and b) stated that RTD data were most useful in diagnosing axial mixing phenomena in twin-screw extruders, providing the basis for scale up and guidance in improvements of equipment. Hsieh (1990) also described many applications of extruder RTD such as nutrient degradation, food safety, and product quality control.

RTD of the material in an extruder can be determined by using radioactive-tracer and dye-tracer techniques (Harper, 1981).

The important process variables for twin-screw extruders are feed composition, feed moisture, feed rate, screw speed, screw profile, barrel temperature, and die size. Many of these variables have been shown to be important factors affecting the RTD E curve and F curve in the extrusion systems (Altomare and Anelich, 1988; Altomare and Ghossi, 1986; Bruin et al., 1978; Davidson et al., 1983; Fellows, 1988; Kao and Allison, 1984; Lin and Armstrong, 1988; van Zuilichem and Stolp, 1983; van Zuilichem et al., 1973, 1975, 1988a, b, and c; Wolf and White, 1976; Wolf et al., 1986). Of particular interest are the screw profile, feed rate, and screw speed. Therefore, the effects of screw profile, feed rate, and screw speed on RTD F curves were studied.

LITERATURE REVIEW

Residence Time Distributions

The residence time distributions of the material in the extruder are usually described as E curve and F curve (Altomare and Anelich, 1988; Lin and Armstrong, 1988). The E curve gives the exit age distribution and was plotted as normalizal concentration E(t) vs. residence time (t). The cumulative E(t), i.e. F(t), vs. normalized time (residence time/mean residence time) was plotted as F curve.

$$E(t) = \frac{C}{\int_0^\infty c\,dt} \cong \frac{C}{\sum_0^\infty c\Delta t} \qquad (1)$$

$$F(t) = \int_0^t E(t)dt \cong \frac{\sum_0^t c\Delta t}{\sum_0^\infty c\Delta t} \qquad (2)$$

where c is concentration and t is time.

The mean residence time ($\bar{t}$), which represented the mean time of the material spent in the extruder, was given by Smith (1981):

$$\bar{t} = \int_0^\infty tE(t)dt = \frac{\sum_0^\infty tc\Delta t}{\sum_0^\infty c\Delta t} \qquad (3)$$

The variance (σ^2) which represented the square of the spread of the distributions was given by Levenspiel (1972):

$$\sigma^2 \cong \frac{\sum_0^\infty (t-\bar{t})^2 c\Delta t}{\sum_0^\infty c\Delta t} = \frac{\sum_0^\infty t^2 c\Delta t}{\sum_0^\infty c\Delta t} - \bar{t}^2 \qquad (4)$$

Effect of Screw Profile

Four sets of screw configurations were studied by Kirby et al. (1989). The mean residence time increased from 56 s to 94 s with increasing the conveying efficiency of the screws. They pointed out that increasing the screw profile's conveying efficiency results a decrease in the mean residence time.

Kao and Allison (1984) observed that the screw configuration also affects the mean residence time. The all-screw bushing screw configuration conveys material faster than the kneading block loaded screw configuration. The reduction is larger at low throughput.

Two kinds of screw profile, moderate and severe, were used by Altomare and Ghossi (1986), to demonstrate the significant effects of screw profiles on residence time distribution. They indicated that the more severe screw profile has lengthened the average residence time and apparently has broadened the distribution.

The screw composition affects mass flow just in front of the last 50 mm screw element was reported by Olkku et al. (1979). Varying screw composition do not affect the impulse responses at the first three detectors (total are five detectors), and only screw revolution and feed rates have an effect on RTD at 300 mm from the inlet.

In 1988, Altomare and Anelich reported that screw pitch has very little effect on extruder performance, at least in an unfilled system. The "gentle" screw profiles consisting of essential screw elements are better mixers than intense screw profiles containing many "mixing" elements. Offset, 1/4 turn, forward and reversing screw elements are extremely effective in generating heat and lengthening residence time.

Usually, screw profile is also an important factor affecting the RTD. Different screw composition, especially in the last extruder zone, results in different RTD.

Effect of Feed Rate (or Throughput)

The throughput during the extrusion can be regulated by changing screw speed or feed hopper rotational speed.

In the experiments of extrusion with styrene-based copolymer, Kao and Allison (1984) observed that the throughput had the largest effect on the mean residence time among all the variables studied (throughput, screw speed, screw configuration, and barrel temperature). Increasing the throughput reduces the mean residence time. For the first screw configuration (containing four kneading block mixing sections), the increase in throughput from 4.54 kg/hr to 13.6 kg/hr reduced the mean residence time by about 70 s. For the second screw configuration (consisting only of regular screw bushings), the reduction was about 40 s.

The influence of feed rate on residence time was also investigated by Altomare and Ghossi (1986). The higher the feed rate, the more uniform the residence time. It appeared that at the lower feed rate where the extruder was less filled, there was less tendency for the extruder to provide positive conveyance. High feed rate provided a sharp RTD distribution with low variance, and low feed rate resulted in a flat RTD distribution with a large variance.

Lin and Armstrong (1988) pointed out that changing feed hopper rotational speeds from 3 rpm to 15 rpm slightly changed the output rate from 0.19 kg/min to 0.22 kg/min.

The other study showed that both the mean residence time and the minimum residence time decreased by only 5% when the feed rate was changed from choke feeding (60 g/s) to starved feeding (30 g/s). With maize grits, an increase in the feed rate decreased the spread of the residence time distribution. The influence of the feed rate on RTD was small (van Zuilichem et al., 1988a, b, and c).

Generally, feed rate is an important factor affecting the RTD. Many reports show that the feed rate has strong effect on the RTD. Increasing the feed rate decreases the mean residence time.

Effect of Screw Speed

Screw speed is one of the most flexible process variables in food extrusion system. It can be easily changed during the operation of the extruder.

In the extrusion of ground maize, van Zuilichem et al. (1973) indicated that the mean residence time decreases from 46 s to 36 s with increasing screw speed from 80 rpm to 120 rpm. In their others studies (1988a, b, and c), they showed that there are linear inverse correlations between mean residence time and screw speed for both soya and maize. The screw speed is the most important variable affecting the mean residence time.

In Lin and Armstrong's experiment (1988), the extrudate output rate increased from 0.22 kg/min to 0.31 kg/min while the screw speed was changed from 100 rpm to 140 rpm. The change in output rate is found to be proportional to screw speed. It appears that increasing the screw speed from 100 rpm to 140 rpm does not change the viscosity of the material in the extruder as evidenced by the die temperature and pressure being unchanged during the extrusion.

They indicated that screw speed affected the residence time most among the extrusion variables studied (feed composition, feed moisture, barrel temperature, screw speed, and throughput).

Davidson et al. (1983) pointed out that the RTD is primarily affected by the screw speed. A change in the screw speed shifts the distribution. At 100 rpm, the mean residence time is approximately 60-65% of the mean at 50 rpm.

Screw speed was second in importance to affect the RTD in sytrene-based copolymer extrusion (Kao and Allison, 1984). The reduction in the mean residence time is approximate 30 s when the screw speed changes from 115 rpm to 492 rpm.

Altomare and Ghossi (1986) reported that raising the screw speed from 150 rpm to 400 rpm shorten the mean residence time from 26.4 s to 20.2 s and shift the RTD curve to the left. The variation of screw speed, despite its influence on temperature and viscosity, has little influence to alter the shape of the dimensionless RTD and overall mixing pattern.

Five screw speeds (36, 42, 60, 83, and 101 rpm) were used to test the effect of screw speeds on the RTD in polymers extrusion (Wolf and white, 1976). However, they found out that no significant effect occurs between the screw speed and the residence time distribution.

A lot of reports pointed out that the screw speed is the most important factor affecting the RTD. Generally, increasing the screw speed results a decrease in the mean residence time.

MATERIALS AND METHODS

Materials

Rice flour (RL-100, RIVLAND, Stuttgart, AK) with moisture content of 20.0% (wet basis) was used as the feed material. Red dye (FD&C, #40, Warner Jenkinson, St. Louis, MO) was chosen as a tracer to measure the residence time distributions of the rice flour in a twin-screw extruder.

Extruder

A co-rotating and intermeshing APV Baker MPF50/25 twin-screw extruder (APV Baker Inc., Grand Rapids, MI), as shown in Figure 1, was used in this study. The power of this machine is

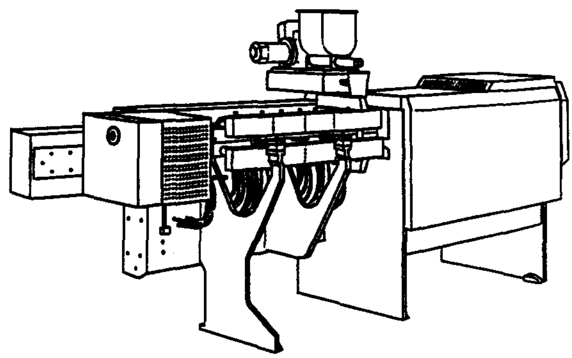

Fig. 1. The APV Baker MPF50/25 twin-screw extruder (Source: Hsieh and Hu, 1990. Agricultural Engineering Department, University of Missouri-Columbia, USA).

28.0 KW (kilowatt) and the total length: diameter ratio is 25:1. The barrel diameter is 50 mm. There are nine temperature controlled barrel sections, and six sections were used (Hsieh et al. 1990). The barrel temperature was set at 26.7°C (feeding zone), 51.7°C, 93.3°C, 121.1°C, and 121.1°C (80, 125, 200, 250, and 250°F) respectively throughout the experiments. The maximum screw speed of this machine was 500 rpm. The die size was 3.175 mm (1/8 in.). Rice flour was fed into the extruder with a K-tron Type T-35 twin-screw volumetric feeder with a Series 6300 controller (K-tron Corp., Pitman, NJ). The adjustable cutter with four blades was operated at 325 rpm. A computer data acquisition system was used to record feed rate, barrel and product temperatures, die pressure and temperature, % torque, screw speed and cutter speed. It took about 15 minutes for the extruder to reach the steady state after start-up.

Experimental design

The process variables chosen in this study were screw profile (7:5, 9:3, and 11:1, i.e., the number of forward screw paddles to reverse paddles in the extruder metering zone), feed rate (30, 40, and 50 kg/hr), and screw speed (200, 300, and 400 rpm). Two replications were used in this completely randomized 3x3x3 factorial experiment. For each treatment, 33 samples were collected in 6 minute intervals to determine the RTDs of rice flour in the extruder.

Standard Curve Experiment

A standard curve of this study was established by a separate experiment. Rice flour and red dye were mixed in a HOBART N50 mixer (Hobart Canada Inc., North York, Ontario, Canada) to different dye concentrations of 0.0%, 0.01%, 0.025%, 0.05%, 0.075%, 0.1%, 0.15%, 0.2%, 0.4%, and 0.6% (w/w). The mixtures were extruded in a MPF 50/25 twin-screw extruder at 20% moisture (w.b), 40 kg/hr and 300 rpm. AS the extruder reached the steady state, a timer was started. Samples for each mixture were collected in one minute intervals from the 4th to 6th minutes. The color values L, a, and b ("L" measures lightness, "a" measures redness, and "b" measures yellowness) of each sample were measured according to the method described below, and the concentrations (g color/100g rice flour) vs. redness color values were plotted as the standard curve for the experiment.

Collection of Samples and Color Measurement

In the study of the 3x3x3 factorial experiment, samples of each treatment were collected as the extruder reached the steady state. One gram of red dye was suddenly dropped into the extruder as a tracer, and a timer was started at the same time. Meanwhile, the extrudate samples were collected for up to 6 minutes (10 s intervals in the first 30 s, 5 s intervals in the next 60 s, 10 s intervals in the following 90 s, and 20 s intervals in the last 180 s). Therefore, 33 samples were collected for each treatment. Each sample was ground by a Waring Blender (New Hartford, CT) and passed the Taylor standard screen (No. 8). The color values (L, a, and b) for each ground sample were measured and recorded using a HunterLab D25 colorimeter (Hunter Associates Lab., Inc., Reston, VA0. A white title (standard No. C2-28656) with values of L= 91.2, a= –0.9, and b= –0.7 was used to standardize the colorimeter. For each sample, two petri dishes with ground extrudates were measured, and two color readings (L, a and b) were recorded for each dish. The second reading was obtained after a 90° rotation of the first reading. Therefore, four readings of color values L, a and b, respectively, were recorded for each sample.

Data analysis

A Fortran 77 program was written to convert the redness color values to concentrations according to the standard curve. The LOTUS 1-2-3 computer software (Lotus Development Corporation, MA, 1986) was used to determine the residence time distributions for each treatment. The F curves of this study for the 3x3x3 factorial experiment were plotted using computer graphics software package (Sigmaplot, version 3.1, Jandel Scientific, 1987).

RESULTS AND DICUSSION

The F curves of residence time distributions were plotted as cumulative E(t), i.e., F(t), versus normalized time (residence time/mean residence time). Almost all residence time distribution models are represented by the F(t) function. The F(t) function was calculated according to equation (2). All the calculations were conconducted using Lotus 1-2-3, and all the figures were plotted using Sigmaplot.

F Curves of Each Treatment

The F curves for each treatment of the 3x3x3 factorial experiment were plotted as F(t) versus $t/\bar{t}$. The F curves of the lowest feed rate and screw speed (30 kg/hr and 200 rpm) for screw profile 7:5, the medium feed rate and screw speed (40 kg/hr and 300 rpm) for screw profile 9:3, and the highest feed rate and screw speed (50 kg/hr and 400 rpm) for screw profile 11:1 are plotted in Figures 2 through 4.

The effects of screw profile, feed rate, and screw speed on the residence time distribution were previously discussed (Peng, 1992a and b). The F curve was important for the residence time

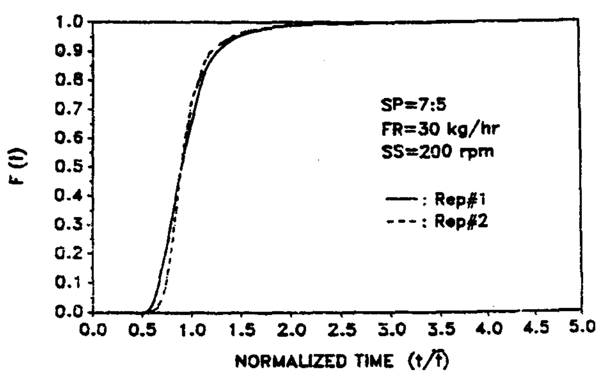

Fig. 2. F curves of 7:5 screw profile, 30 kg/hr feed rate, and 200 rpm screw speed.

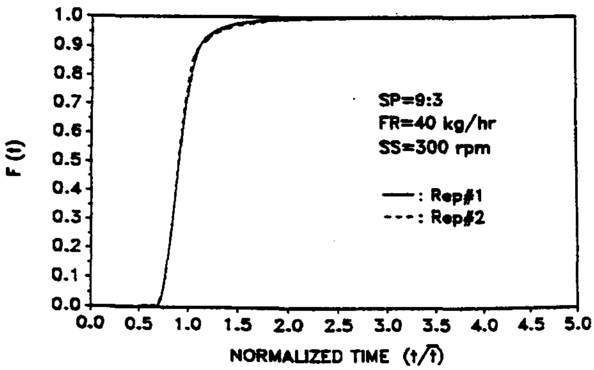

Fig. 3. F curves of 9:3 screw profile, 40 kg/hr feed rate, and 300 rpm screw speed.

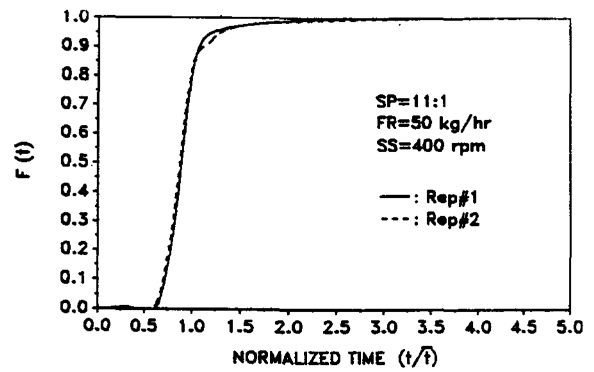

Fig. 4. F curves of 11:1 screw profile, 50 kg/hr feed rate, and 400 rpm screw speed.

distribution modeling. The slope of the F curve was the steepest at the highest feed rate, screw speed, and 11:1 screw profile. The slope increased with increasing feed rate, screw speed, and the number of forward paddles in the extruder metering zone. The initial point of the F curve for F(t) > 0 was found to be about 0.5 of the normalized time for screw profile 7:5 (Figure 2), and about 0.6-0.7 of the normalized time for screw profile 9:3 and 11:1 (Figure 3 through 4). The F curve of the higher screw profile, feed rate, and screw speed was steeper than the lower screw profile, feed rate, and screw speed. Comparing the results with Peng (1992b), it was found that a steeper F curve reflects shorter mean residence time. Comparing screw profile 7:5, feed rate 30 kg/hr, and screw speed 200 rpm (Figure 2) with 11:1, 50 kg/hr, and 400 rpm (Figure 4), the former F curve was less steep than the latter, i.e., the mean residence time of the former was longer than the latter. The phenomena matched the results shown in Peng (1992b).

Comparison of F Curves with Different Screw Profiles

The F curves of different screw profiles (7:5, 9:3, and 11:1) with feed rates and screw speeds at 30 kg/hr and 200 rpm, 40 kg/hr and 300 rpm, and 50 kg/hr and 400 rpm are shown in Figure 5 through 7.

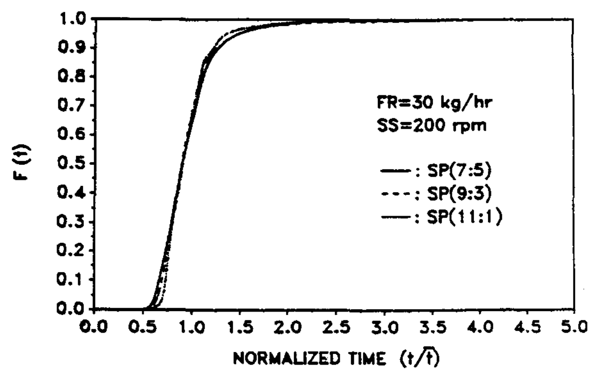

Fig. 5. F curves of different screw profiles at 30 kg/hr feed rate and 200 rpm screw speed.

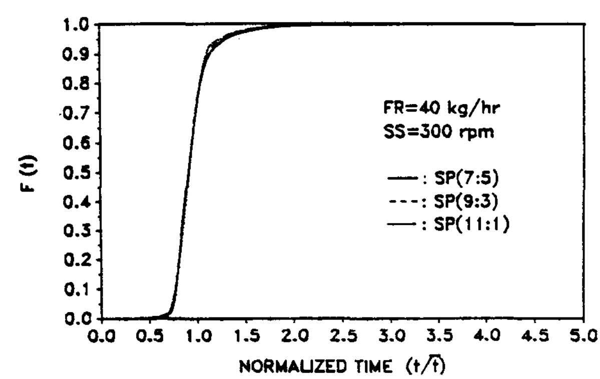

Fig. 6. F curves of different screw profiles at 40 kg/hr feed rate and 300 rpm screw speed.

The effects of screw profiles on the residence time distribution were previously discussed (Peng, 1992b). All the F curves from Figure 5 through 7 with screw profile 7:5, 9:3, and 11:1 were almost identical. These phenomena showed

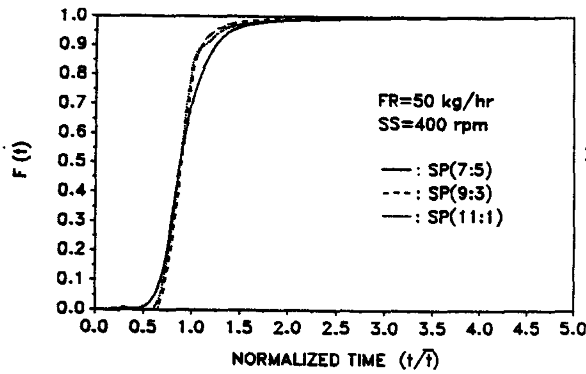

Fig. 7. F curves of different screw profiles at 50 kg/hr feed rate and 400 rpm screw speed.

that the screw profile affecting the F curves least. The results were in agreement with those reported by Kirby et al. (1989), Kao and Allison (1984), Altomare and Ghossi (1986), and Olkku et al. (1979).

Comparison of F Curves with Different Feed Rates

The F curves of different feed rates (30 kg/hr, 40 kg/hr, and 50 kg/hr) with screw profiles and screw speeds at 7:5 and 200 rpm, 9:3 and 300 rpm, and 11:1 and 400 rpm are shown in Figure 8 through 10.

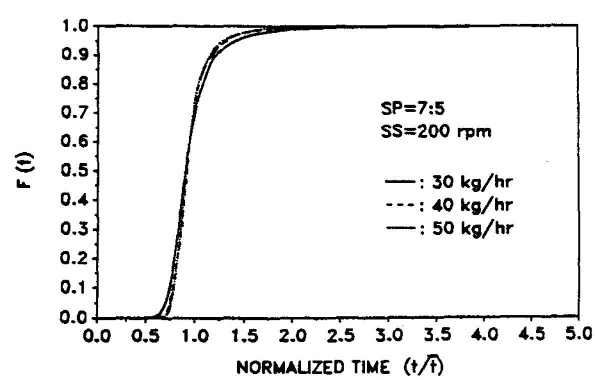

Fig. 8. F curves of different feed rates at 7:5 screw profile and 200 rpm screw speed.

The effects of feed rates on the residence time distribution were also discussed (Peng, 1992b). All the F curves shown in Figure 8 through 10 with feed rates of 30 kg/hr, 40 kg/hr,

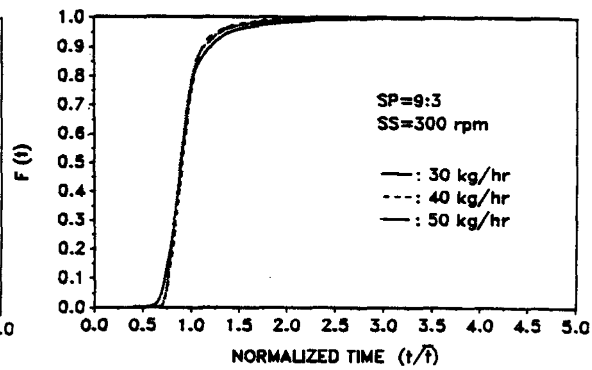

Fig. 9. F curves of different feed rates at 9:3 screw profile and 300 rpm screw speed.

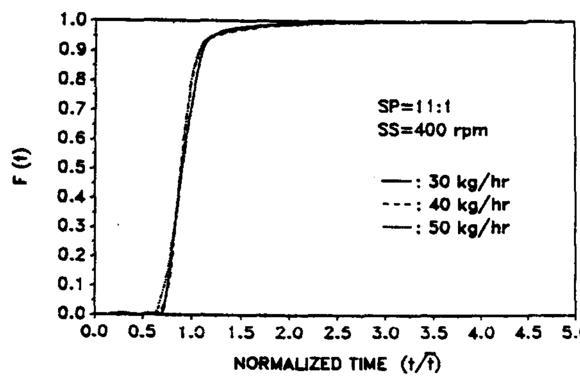

Fig. 10. F curves of different feed rates at 11:1 screw profile and 400 rpm screw speed.

and 50kg/hr were similar. However, the F curve of the lower feed rate was less steep than the higher feed rate in each plot. This reflects that the mean residence time of the lower feed rate was longer than the higher feed rate. All the F curves of those plots did not change much even though the higher feed rate had a steeper F curve than the lower feed rate at each plot. The F curves reflected that the screw profile was the least important factor affecting the RTD. The restults were the same as Kao and Allison (1984), Altomare and Ghossi (1986), Lin and Armstrong (1988), and van Zuilichem et al. (1988a, b, and c).

Comparison of F Curves with Different Screw Speeds

The F curves of different screw speeds (200 rpm, 300 rpm, and 400 rpm) with screw profiles and feed rates at 7:5 and 30 kg/hr 9:3 and 40 kg/hr, and 11:1 and 50 kg/hr are shown in Figure 11 through 13.

The effects of screw speeds on the residence time distribution were discussed (Peng, 1992b). All the F curves with screw speed of 200, 300, and 400 rpm in Figure 11 through 13 were almost identical. However, the F curve of the higher screw speed was steeper than the lower screw speed in each plot. This reflects that the mean residence time of the lower screw speed was longer than the higher screw speed. The results were in agreement with the results shown in Van Zuilichem et al. (1973, 1988a, b, and c), Lin and Armstrong (1988), and Davidson et al. (1983).

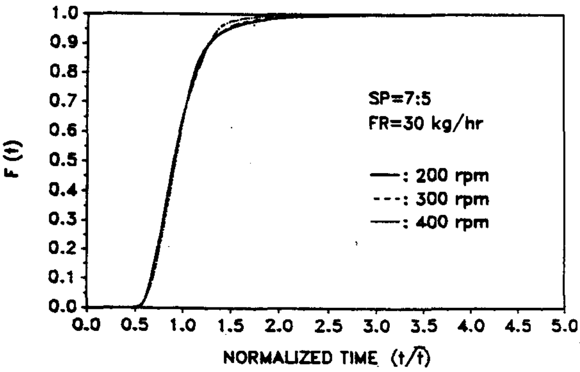

Fig. 11. F curves of different screw speeds at 7:5 screw profile and 30 kg/hr feed rate.

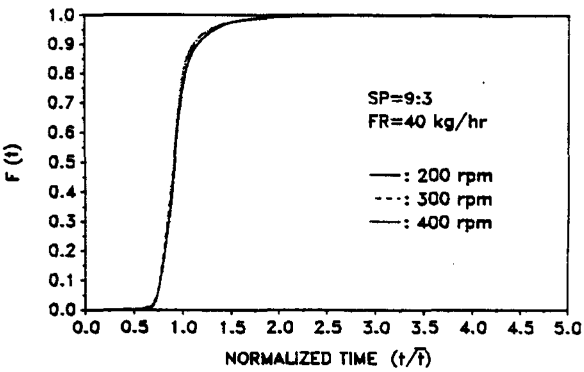

Fig. 12. F curves of different screw speeds at 9:3 screw profile and 40 kg/hr feed rate.

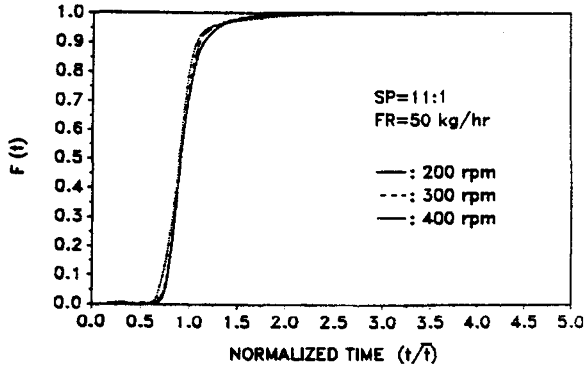

Fig. 13. F curves of different screw speeds at 11:1 screw profile and 50 kg/hr feed rate.

CONCLUSION

A colorimetric method was used to study the residence time distribution (RTD) in an APV Baker MPF50/25 twin-screw extruder using rice flour as the feed material. The process variables were screw profile, feed rate, and screw speed. A 3x3x3 factorial experiment was designed to study the effects of process variables on RTD F curves.

The effects of process variables on the mean residence time were significant. In general, increasing the number of forward paddles in the extruder metering zone, feed rate, or screw speed decreased the mean residence time and steeper the F curves. The most important factor affecting the RTD F curves was feed rate. Screw profile was the second important factor and screw speed was the least important factor affecting the RTD F curves in this research.

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