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Effect of screw configuration and speed on the P estimate of residence time distribution flow models

(Kesan konfigurasi dan kelajuan skru terhadap anggaran P model aliran penahanan masa pengagihan)

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Key words: extrusion, residence time distribution, P estimate, flow models

Abstrak

Pemasakan penyemperitan beras semakin popular kerana sifat pengembangan beras dan perisanya yang sederhana. Mil beras (25% lembapan basah) disemperitkan dengan menggunakan mesin penyemperit 30 mm skru kembar sepemutaran. Profil suhu 30, 60, 100 dan 130 °C sepanjang mesin penyemperit dan 130 °C digunakan pada bahagian acuan. Tiga konfigurasi skru dan lima kelajuan skru berjulat antara 62.5 rpm dengan 162.5 rpm digunakan. Penahanan masa pengagihan (PMP) ialah cara yang berguna untuk mengukur corak aliran bahan di dalam mesin penyemperit. PMP telah dianalisa dengan menggunakan pewarna merah natrium eritrosin. PMP dimodelkan dengan menggunakan gabungan aliran campuran sempurna dengan anggaran P (sebahagian kecil bahan dalam aliran sumbat) 0.5 dan aliran sumbat dengan anggaran P 1.0. Dalam kajian ini, aliran di dalam mesin penyemperit dimodelkan dengan anggaran P berjulat 0.41–0.55. Kelajuan skru didapati mempunyai kesan yang bererti terhadap anggaran P.

Abstract

Extrusion cooking of rice has gained popularity due to the expansion properties and mild flavour of rice. Rice meal (25% wb moisture) was extruded using a 30 mm corotating twin screw extruder. The temperature profile used was 30, 60, 100 and 130 °C along the extruder and 130 °C at the die section. Three screw configurations and five screw speeds ranging from 62.5 rpm to 162.5 rpm were used. Residence time distribution (RTD) is a useful means to quantify the flow pattern of material in an extruder. RTD was analysed using the red dye intensity of sodium erythrosin. The RTD flow was modeled by combining perfect mixed flow and plug flow where P estimate (the fraction of material in plug flow) equaled to 0.5 and 1.0 respectively. In this study, the flow through the extruder was modeled by P estimate in the range of 0.41–0.55. Screw speed was found to have a significant effect on the P estimate.

Introduction

Extrusion cooking is a process whereby moistened, starchy and/or proteinaceous foods are cooked and worked into a viscous, plastic-like dough. Cooking is accomplished through the application of heat, either directly by steam injection or indirectly through jackets, and by dissipation

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of the mechanical energy through shearing of the dough (Harper 1981).

The many advantages of extrusion cooking resulted in the rapid acceptance of the extruder as an important food processing machine. Besides its high productivity because it cooks and forms in a single processing step, as well as its cost effectiveness, the extruder can handle a wide variety of raw materials (Harper 1978).

The independent variables of extrusion process are screw speed, screw configuration, temperature, moisture content and mass flow rate. These variables can considerably affect the product temperature profile, residence time distribution and shear history of the product which are commonly known as dependent system variables. Thus, an experiment was conducted to study the effects of three screw configurations and five screw speeds on the residence time distribution flow models of rice meal in a corotating twin screw extruder.

Rice meal is a constituent of broken rice which is easily available and is relatively inexpensive. Rice can expand well and its bland flavour makes it desirable for preserving more expensive flavour attributes (Hubert and Rokey 1990). Thus, rice is an excellent choice for the production of extrusion snack.

Literature review

Extrusion cooking is a specialized form of a high-temperature short-time (HTST) reaction. A unique aspect of such cooking is the ability to extrude relatively dry materials which are usually pre-mixed and preconditioned. After being introduced into the heated screw, the mixture is transported, compressed and worked to form a semi-solid mass in the barrel by means of one or more rotating screws. This process reduces microbial load, inactivates enzymes, gelatinizes starch, polymerizes proteins and most important, textures the end products into a desirable form (Fichtali and van de Voort 1989; van Lengerich 1990).

One way to evaluate the time-temperature treatment of the product in the extruder is through residence time distribution (RTD). The RTD in an extruder is a useful means of determining optimal processing conditions for mixing, cooking and shearing reactions during the process. From the RTD functions, one can estimate the degree of mixing, the life expectancy of mass flow and the average total strain exerted on the mass during its transition, thus providing a clear picture of how an extruder behaves as a chemical reactor (Fichtali and van de Voort 1989). These results, coupled with the knowledge of the operating variables such as temperature, screw speed, screw configuration and moisture content, provide necessary information to predict the fraction of the material undergoing specific reactions.

The RTD is commonly described by the *F*-diagram and the *E*-diagram. The *F*-diagram is the response of the system when a stepwise change in inlet concentration (e.g. a tracer) is made while the *E*-diagram is the response of the system to a pulse-like injection of a tracer at the inlet (Bruin et al. 1978).

It is possible to analyse and compare the mixing and conveying behavior of different types of twin screw extruders by fitting the RTD data into an appropriate mathematical model. The most appropriate model is based on the combination of perfect mixing and plug flow developed by Wolf and White (1976). Typical values of P estimate (the fraction of material in plug flow) are 0.75 (Bruin et al. 1978) for a single screw extruder, 0.50 (Altomare and Ghossi 1986) for a twin screw intermeshing corotating extruder and 0.92 (Lin and Armstrong 1990) for an intermeshing counter rotating twin screw extruder.

Wolf and White (1976) studied the effect of screw speed and screw temperature on the RTD of a plastic extruder. They concluded that the screw speed has no significant effect on the RTD and that the RTD function of solid conveying process is very close to plug flow where the P estimate equals 1.0.

Kao and Allison (1984) studied the throughput, screw speed, barrel temperature and two screw configurations on the RTD of a fully intermeshing corotating twin screw extruder. One of the screw configurations studied employed a large number of kneading blocks in four separate mixing sections, representing the case where extensive compounding was required. Another screw configuration studied consisted entirely of regular screw, representing the other extreme with no additional mixing. They concluded that the screw configuration with four kneading sections showed a flow characteristic closer to the plug flow model (P estimate = 1.0) than the plain screw configuration.

Wolf et al. (1986) studied the RTD of polyvinyl chloride (PVC) polymers at different cross-sections along the length of the screws in a commercial counter rotating twin screw extruder. Their results showed counter rotating twin screw extruders have unusually near plug flow profiles along almost the entire extruder length.

RTD can generally be described by two closely-related functions: the *E(t)* and *F(t)* diagrams (Levenspiel 1972). The response of the extruder to a pulse at the inlet is given by an *E(t)* diagram which represents the age distribution of the material in the extruder. Since it is difficult to ensure that the same amount of tracer is used in all experiments, it is common to normalize the tracer concentrations at each point in time by dividing them by the total amount of tracer passed through the system. Thus, the *E(t)* diagram can be obtained by dividing the concentration, at any time interval, by the total amount of tracer injected.

$$E(t) = \frac{c_i}{\int_{i=0}^{\infty} c_i dt} \approx \frac{c_i}{\sum_{i=0}^{\infty} c_i \Delta t} \qquad \text{(i)}$$

where c = tracer concentration at time t

The *F(t)* diagram which is related to the *E(t)* diagram, represents the cumulative distribution function in the exit stream at any time. It is given by

$$F(t) = \int_{i=0}^{i=t} E(t)dt \approx \sum_{i=0}^{i=t} c_i \Delta t \div \sum_{i=0}^{i=\infty} c_i \Delta t \qquad \text{(ii)}$$

The mean residence time (t), the mean time the material spent in the extruder, is given by

$$\bar{t} = \int_{i=0}^{i=t} t_i E(t)dt \cong \sum_{i=0}^{i=\infty} t_i c_i \Delta t \div \sum_{i=0}^{i=\infty} c_i \Delta t \qquad \text{(iii)}$$

For comparison purposes, it is convenient to normalize the functions by the mean residence time. Thus,

$$\theta = t/\bar{t} \qquad \text{(iv)}$$
$$E(\theta) = \bar{t}\, E(t) \qquad \text{(v)}$$
$$F(\theta) = F(t) \qquad \text{(vi)}$$

The RTD data was used to fit a combination of perfect mixed flow and plug flow model developed by Wolf and White (1976) as given by

$F(\theta) = 1 - e^{[-1/(1-P))(\theta-P)]}$ for $\theta \geq P$
$F(\theta) = 0$ for $0 < \theta < P$

where θ = dimensionless time
P = fraction of material in plug flow, which is also known as the P estimate of the RTD flow models

Materials and methods

Extrusion trials were performed using a MPC/V-30 corotating twin screw extruder (APV, Staffordshire, England) with a System90 torque rheometer (Haake Buhler, Paramus, NJ). The twin screw extruder had a length to diameter ratio (L/D) of 13. A slit rheometer capillary die (Haake Buhler, Paramus, NJ) was attached to the twin screw extruder. The slit die provided four ports for placement of three PT422A Dynisco pressure transducers (Sharon, MA) and one melt thermocouple probe Type J (Omega Engineering, Westport, CT). The ranges of pressure transducers were 0–10.342 x10^6 N/m^2 at the first port, 0–6.895 x 10^6 N/m^2 at the second port and 0–3.447 x 10^6 N/m^2 at the third port of the slit die. The dimensions of the slit die were 1.47 mm high and 20 mm wide. The die produced a strip of cooked material during extrusion. The MPC/V-30 consisted of a clam-shell barrel with four independent zones, an adapter piece and a die at the end which could be independently heated. The barrel section can be heated with electrical coils and cooled separately with compressed air. Melt temperatures were measured by four thermocouples along the barrel, and one each at the adapter piece and the die section. The heater temperature range was 0–400 °C. A computerized data acquisition system was used to acquire the temperatures (melt and set temperatures), pressure, screw speed and torque at a sampling rate of 6 s.

In these experiments, rice meal (Pacific Grain Products, Woodland, CA) was metered at 30 g/min by a K-Tron Model T-20 volumetric feeder (K-Tron Corp., Pitman, NJ). Its fractional wet weight basis (wb) moisture content of the rice meal was determined by the AOAC method 925.09 (AOAC 1990). Water was added slowly to bring the rice meal to the required moisture content of 25% while being mixed at medium speed in a Hobart mixer, Model N-5 (Hobart Corp., Troy, OH). The samples were then sealed in polyethylene bags and stored in the cold room at 5 °C for a minimum of 24 h but not more than 72 h to reach equilibrium. The samples were then allowed to equilibrate to room temperature before feeding them into the extruder.

Preliminary trials were performed to choose the temperature profile of the extruder needed to produce extrudates with acceptable physical properties (solid foam without burning). Temperature profile of 30, 60, 100 and 130 °C at the first, second, third, fourth sections and 130 °C at the die section was suitable.

Based on preliminary experiments, three screw configurations and five screw speeds were chosen for this research. The screw configurations were designated low, medium and severe depending on the number of mixing paddles incorporated and their position *(Table 1)*. The five screw speeds were 62.5, 87.5, 112.5, 137.5 and 162.5 rpm.

Split plot experimental design was used *(Table 2)*. With three replicates within each

Table 1. Screw configurations

Low screw configuration			Medium screw configuration			Severe screw configuration		
Section	Orientation	L/D	Section	Orientation	L/D	Section	Orientation	L/D
F	–	1.5	F	–	1.5	F	–	1.5
F	–	1.5	F	–	1.5	F	–	1.5
F	–	1.5	F	–	1.5	F	–	1.5
F	–	1.5	F	–	1.5	F	–	1.5
F	–	1.5	F	–	1.5	F	–	1.5
F	–	1.5	F	–	1.5	F	–	1.5
F	–	1.0	M	30° *f*	0.25	F	–	1.0
F	–	1.0	M	60° *f*	0.25	F	–	1.0
F	–	1.0	M	90° *f*	0.25	M	30° *f*	0.25
D	–	1.0	F	–	1.0	M	60° *f*	0.25
			M	90° *f*	0.25	M	90° *f*	0.25
			F	–	1.0	M	30° *f*	0.25
			D	–	1.0	D	–	1.0

F = feed screw
D = discharge screw
f = forward
M = mixing paddles
L/D = length/diameter ratio

Table 2. Split plot experimental design

Replicate	Exp.	Screw configuration	Five screw speeds (rpm)				
			1	2	3	4	5
1	1	Low	137.5	162.5	112.5	62.5	87.5
	2	Severe	137.5	162.5	87.5	62.5	112.5
	3	Medium	62.5	162.5	87.5	112.5	137.5
2	1	Medium	137.5	112.5	87.5	62.5	162.5
	2	Low	87.5	137.5	62.5	162.5	112.5
	3	Severe	87.5	112.5	137.5	62.5	162.5
3	1	Medium	87.5	162.5	112.5	62.5	137.5
	2	Severe	112.5	162.5	62.5	137.5	87.5
	3	Low	62.5	137.5	162.5	87.5	112.5

replicate, the screw configurations were randomly assigned to the three experiments. Within each screw configuration, the screw speeds were randomly chosen using Ten Thousand Randomly Assorted Digits (Snedecor and Cochran 1976).

The RTD study was performed by using a dye technique as a tracer (Lin and Armstrong 1990). The tracer was prepared by mixing 0.025 g of red dye, sodium erythrosin (Sigma Chemical Co., St. Louis, MO) with 10.0 g of rice meal and the amount of water needed to bring the moisture content of the tracer to that of the feed material (25% wb). These tracer samples were sealed in polyethylene cups and stored in the cold room at 5 °C for a minimum of 24 h but not more than 72 h to equilibrate. The tracer samples were then allowed to equilibrate to room temperature before extrusion. To produce smooth RTD curves, tracer samples were collected at every 20-s interval for the first 5 min and the first 20-s interval for the next 10 min which gave a total of 30 sampling points. Results obtained showed that the experiments were reproducible.

On steady state conditions (indicated by constant temperature, pressure and torque measurements), a strip of the extrudate was cut to be used as a control for color measurement. The tracer sample was then added as a pulse input through the inlet port of the extruder. At the same instant, a timer was started and a length of extrudate was cut at an interval of 20-s for a duration of 15 min. All samples for the first 5 min and then every first sample for the sixth to the 15th min were selected for color measurement.

All the samples including the control sample were dried overnight in a forced air oven at 60 °C to equilibrate the moisture. The dried samples were ground in a IKA-analytical mill A10 (Type A10S2, Staufen, Germany). The ground material was then sieved through a 50 US standard sieve (Newark, NJ). The uniform powder was analysed for color intensity on a spectrophotometer CM-2002 (Minolta Corp., Ramsey, NJ). Measurements were calculated based on the 2° Standard Observer D65 illuminant and were displayed in L^*, a^*, b^* values which were registered and stored in the memory card, where L^* = total lightness, a^* = red to green and b^* = yellow to blue. Each measurement was automatically averaged from three readings. The red color intensity was used as the 'index of saturation' (Francis and Clydesdale 1975) for RTD functions,

$$c = [(\Delta a)^2 + (\Delta b)^2]^{1/2}$$

where, c = index of saturation
$\Delta a = (a^*\text{standard}) - a^*$
$\Delta b = (b^*\text{standard}) - b^*$

Results and discussion

Before the RTD data were calculated, dye calibration curves for raw rice meal and extruded rice meal were compared for significant differences in color intensity. It was found that there were no significant differences between the two.

As mentioned earlier, it is possible to analyse and compare the mixing and conveying behavior of different types of twin screw extruders by fitting the RTD data to a combination of perfect mixing and plug flow model developed by Wolf and White (1976). Using this model, it is possible to obtain the P estimate which represents the fraction of material in plug flow. Knowing the P estimate and coupled with the conditions of extrusion, basically the operating variables, one can predict the fraction of the material which undergoes specific reactions.

The AR-Derivative-free nonlinear regression (BMDP Statistical Software, Inc., Los Angeles, CA) was used to analyse the P estimate of the RTD flow models. SuperANOVA (Abacus Concepts, Inc., Berkeley, CA) was used to analyse the statistical analysis of P estimate. Results included an analysis of variance table, means table and Duncan New Multiple Range table on the significant effect. Plots were also produced to compare the predicted and experimental values as well as to show the residuals.

From the ANOVA table *(Table 3)*, it was found that speed was highly significant on the P estimate of the RTD flow models.

Table 4 shows that screw speed is inversely proportional to the P estimate. As speed increased from 62.5 rpm to 162.5 rpm, the P estimate decreased from 0.551 to 0.406. Therefore, an average value of 0.48 from all the P estimate values was used to fit the experimental data i.e. $F(\theta)$ to the model developed by Wolf and White (1976). The P estimate of 0.48 was found to give a reasonable fit to the experimental data obtained in all the experiments as shown in *Figure 1* to *Figure 3* with $R^2 = 0.9040$, 0.9021 and 0.9531 respectively. These figures depict the overall flow pattern of the low screw configuration at 62.5, 112.5 and 162.5 rpm respectively. The P estimate of plug flow is 1.0, perfectly mixed flow is 0 and laminar flow is 0.5 in these figures. The P estimate of 0.48 which gave a reasonably good fit to $F(\theta)$ in this models, indicated that the flow in this extruder approaches

Table 3. ANOVA of P estimate of RTD flow models

Source	df	MS	F value
Rep (experiment)	2	0.001	1.110
S. configuration	2	0.006	4.528
Rep x S. configuration	4	0.001	2.141
S. speed	4	0.031	50.831**
S. configuration x S. speed	8	0.001	0.843
Residual	24	0.001	

**Significant at 1% level

Table 4. Effect of mean speed on P estimate of RTD flow models

Screw speed (rpm)	P estimate*	Standard deviation
62.5	0.551 ± 0.006	0.018
87.5	0.486 ± 0.013	0.040
112.5	0.479 ± 0.011	0.034
137.5	0.419 ± 0.011	0.032
162.5	0.406 ± 0.009	0.026

*Mean ± standard error of 9 readings

Table 5. Duncan New Multiple Range of speed on P estimate

Screw speed (rpm)	vs Speed (rpm)	Significance
162.5	137.5	
	112.5	S
	87.5	S
	62.5	S
137.5	112.5	S
	87.5	S
	62.5	S
112.5	87.5	
	62.5	S
87.5	62.5	S

S = significantly different at 5% level

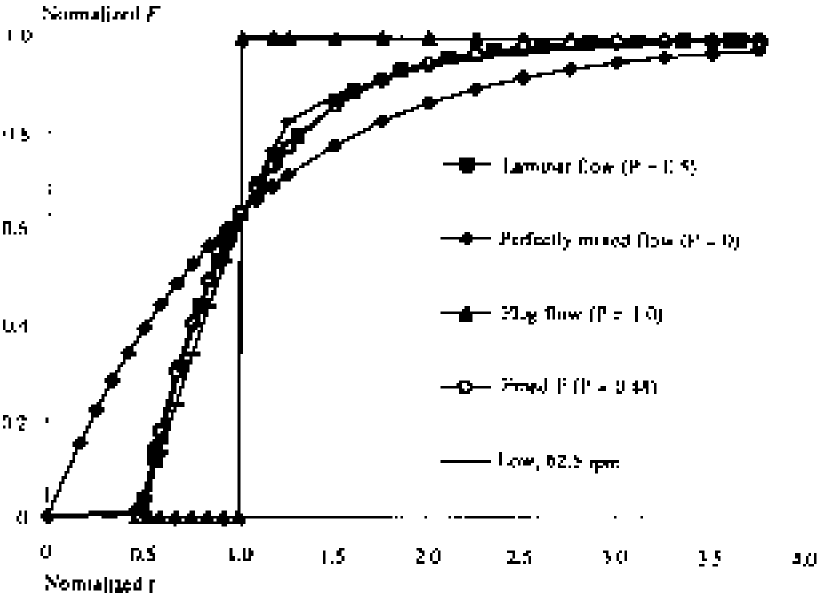

Figure 1. Residence time distribution flow models (low, 62.5)

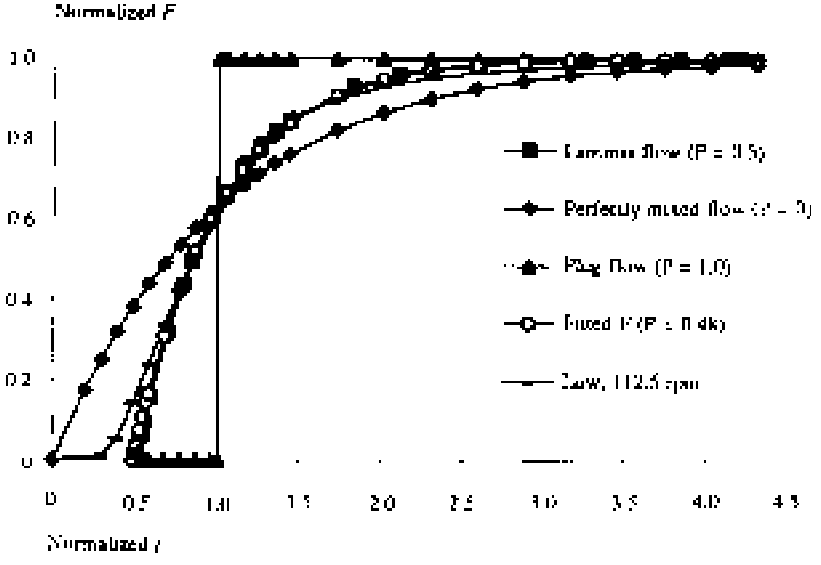

Figure 2. Residence time distribution flow models (low, 112.5 rpm)

laminar flow. Similar results were obtained by Altomare and Ghossi (1986), and Meuser et al. (1987) using the same approach.

The Duncan New Multiple Range of the effect of speed on the P estimate showed that all speeds were significantly different except 162.5 rpm which was not significantly different from 137.5 rpm *(Table 5)*. Screw speed of 112.5 rpm was also not significantly different from 87.5 rpm.

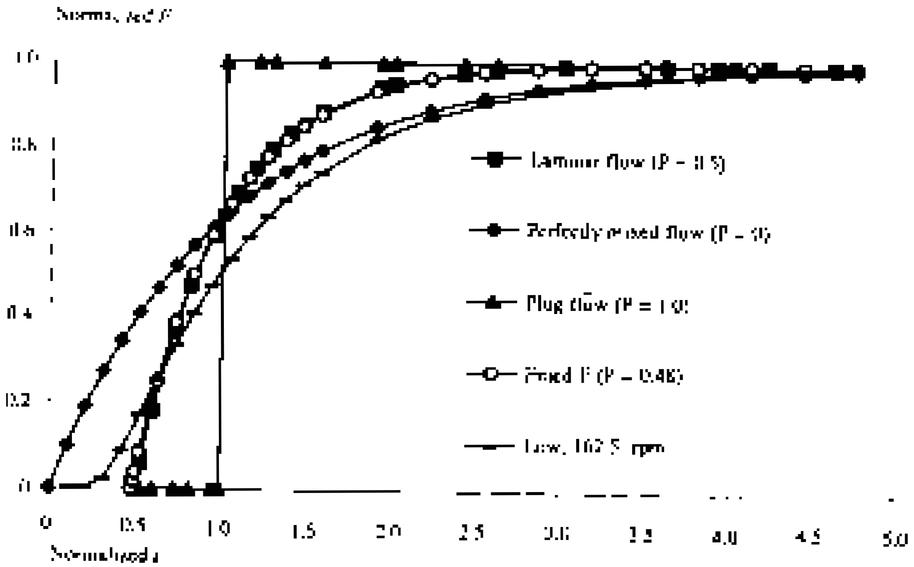

Figure 3. Residence time distribution flow models (low, 162.5 rpm)

Conclusion

The experimental studies on the RTD functions reported here demonstrated that this established dye technique is simple as well as reproducible and can be applied to most extruders. RTD is a useful means to quantify the way material moves through the extruder, how long the individual molecules stay in the extruder, the time-temperature treatment and the cooking of material in the extruder. Modeling of the RTD flow models which indirectly produce the P estimate value, indicates the flow pattern of the extruder. Flow patterns of most extruders lie somewhere between that for laminar flow in a pipe and plug flow, where no back mixing exists. From this experiment, it can be concluded that the P estimate of the RTD flow models is very near laminar flow in a pipe which has a P estimate of 0.5. The P estimate ranged from 0.406 at 162.5 rpm screw speed to 0.551 at 62.5 rpm. The P estimate of 0.48 was found to give a good fit to all the experimental data. Screw speed was found to have a strong significance on the P estimate.

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