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Eefect of Extrusion Variables on Torque, Specific Mechanical Energy, Volumetric Flow Rate and Residence Time of Blends of Acha/Soybean- A Response Surface Analysis

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Abstract: Soybean was sorted, washed, cracked, winnowed and coarsely milled in attrition mill. Acha grains were winnowed and milled similarly. Milled flours were sieved to pass 0.75-1 mm laboratory mesh. The Moisture content of the flours was determined. Soybean flour was added to acha flour at 0, 12.5, 25, 37.5 and 50% levels of substitution. The moisture content of the blends was then adjusted to 15, 20, 25, 30 and 35% levels. The flours were then re-mixed manually and allowed to equilibrate for 3 h. Extrusion was carried out using a Brabender laboratory single-screw extruder (Duisburg DCE -330 model). The screw speed was adjusted from 90 to 120, 150,180 and 210 rpm. The first and second barrel heaters were kept constant at 125°C while the exit heater was adjusted from 100, 125, 150, 175 and 200°C. Acha flour was used to stabilize the extruder before extrusion runs began. Extrusion was carried out following a four variable response surface analysis using a central composite rotatable design that was nearly orthogonal. During extrusion runs, the torque, the residence time and volumetric flow rates of extrudates were obtained. Specific mechanical energy was calculated from the data of torque and volumetric flow rate. The results showed that the torque ranged from 1.33 to 57(NmS) while volumetric flow rate ranged from (10-178 kg S^{-1}). Similarly the specific mechanical energy ranged from (1.76-9.60 KW h^{-1}) while the residence time ranged from (16.23-33.02 sec). The results were indicative that the second other polynomial was not adequate to model the dependence of the torque and specific mechanical energy on the process variables but modelled the dependence of the volumetric flow rate and residence time.

Key words: Flour blends, response surface, process variables and predictive models extrusion

INTRODUCTION

Acha (*Digitaria exillis Skippis Staph.*) is also known as Fonio, fundi or hungry rice in different savannah zones of West Africa. Acha occupies about 300,000 hectares of land in West Africa and provides food for about 4 million people (Kwon-dung and Misari, 2001). It is said to be the oldest West African cereal whose cultivation dates back to about 5000 BC (Pulseglove, 1975). According to Kwon-dung and Misari (2001) acha is one of the world's best tasting cereals and comparison of dishes of acha and rice showed that majority preferred acha dish. The protein content of acha grains is rich in methionine and cysteine (above the recommended levels). These levels are unusual for cereals. With the exception of methionine, the essential amino acid content f acha is lower than in maize, rice sorghum, millet, wheat, barley and oats. Victor and James (1991) therefore advocated its complementation with protein rich foods to make a balanced diet.

Soybeans, (*Glycine max L Merrill*) a versatile pulse constitutes the staple food in many parts of the globe. It is the richest, cheapest and best source of vegetable protein available to mankind. With high protein, high polyunsaturated fat content and absence of cholesterol and lactose, soybean is an excellent source of the essential amino acids vital for body growth, maintenance and reproduction. It is also a good source of minerals and vitamins (Iwe, 2001).

The ability of extrusion cooking to process various plant materials either alone or in blends into foods of high nutritional quality has meant a great deal to food fortification, particularly in the LDCs where diet is mostly derived from cereals or roots (FAO, 1985). The extrusion process is versatile and efficient and is used for converting raw ingredients to intermediate and finished foods. It adds a great value and variety to products and is expected to enhance the production, processing, storage and commercialisation of acha-soybean products for a wide range of uses One of the earliest methods used in extrusion cooking studies was to prepare extruded samples under different conditions and relate a measured property as a function of the processing variables. Inability to detect cross product interaction, examination of large numbers of experiments and difficulty in generalizing the results were some of the limitations of this method. Response Surface Methodology (RSM)

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basic principle is to relate product properties (mechanical, functional, nutritional and sensory) to process variables (geometry, raw material, operating variables). This is done by means of regression equations that describe inter-relations between input parameters and product properties; this is generally done through the use of a statistically designed multifactor experiment for economy of experimental points (Tayeb *et al.*, 1992; Iwe, 2001; Leslie and Dale, 1990; Aguilera and Kosikowski, 1976; Frazier *et al.*, 1983).

There is currently scanty information on the general application of response surface analysis in food research in Nigeria while there is dearth of information on specific application of extrusion technology in acha/soybean formulation processing. The objective of this present study was to develop predictive models that relate extrusion process variables to extruder torque, volumetric flow rate, specific mechanical energy and residence time of extrudates of acha/soybean blends.

MATERIALS AND METHODS

The flours (acha and soybean) were sieved to pass a laboratory sieve mesh of 0.75- 1 mm. The moisture content of the flours were determined (AOAC, 1984) and used to adjust the moisture levels of the blends according to (Wilmot, 1998). Acha and soybean flour were mixed as shown in the extrusion condition profile (Table 1). Extrusion was carried out using a Branbender Laboratory single screw extruder (DUISBURG DCE-330 Model Germany). The grooved band had a length/diameter ratio of 20:1. The extruder had variable screws and heaters with a fixed die diameter of 2 mm and length of 40 mm. A feed hopper mounted vertically above the end of the extruder and equipped with a screw that rotated at a constant speed of 80 rpm on a vertical axis takes feed into the extruder. The wet flour blends were allowed to equilibrate for 2-3 h before extrusion. The extruder runs were stabilized using acha flour. Extrusion of the blends was carried out as shown in the transformed matrix (Table 1).

Experimental design: The experimental design was a 4 variable (central composite rotatable design nearly orthogonal) involving 4 independent variables-Feed Composition (FC), Feed Moisture Content (FMC), Screw Speed (SS) and Barrel Temperature(BT) tested at 5 levels coded (-2 to +2) according to Meyers (1976) and Iwe (2001) Table 1. The experimental design required a total of 36 extruder runs. Sixteen were performed at the factorial points, 8 at the axial points and twelve at the centre points (Table 1). Extrusion condition profile is shown in (Table 1). After steady state conditions were attained, the dependent variables were determined as follows.

Table 1: Matrix transformation of the experimental design runs and extrusion conditions

Feed composition	Feed moisture content	Screw speed	Barrel temperature		
			1	2	Die temp
125	20	120	125	125	125
125	20	120	125	125	175
125	20	180	125	125	125
125	20	180	125	125	175
125	30	120	125	125	125
125	30	120	125	125	175
125	30	180	125	125	125
125	30	180	125	125	175
375	20	120	125	125	125
375	20	120	125	125	175
375	20	180	125	125	125
375	20	180	125	125	175
375	30	120	125	125	125
375	30	120	125	125	175
375	30	180	125	125	125
375	30	180	125	125	175
500	25	150	125	125	150
0	25	150	125	125	150
250	15	150	125	125	150
250	35	150	125	125	150
250	25	90	125	125	150
250	25	210	125	125	150
250	25	150	125	125	100
250	25	150	125	125	200
250	25	150	125	125	150
250	25	150	125	125	150
250	25	150	125	125	150
250	25	150	125	125	150
250	25	150	125	125	150
250	25	150	125	125	150
250	25	150	125	125	150
250	25	150	125	125	150
250	25	150	125	125	150
250	25	150	125	125	150
250	25	150	125	125	150
250	25	150	125	125	150

ANALYSIS

Torque (Ampere Nm): This was determined by reading directly from the extruder operation panel during extrusion runs according to Iwe *et al.* (2001). A value of 2.0A was subtracted from the total obtained, being the motor driving force as reported by Iwe (2001). Three readings were taken for each run except where the Torque was difficult to monitor from the panel. Mean values of torque were expressed in Nm s^{-1}.

Volumetric flow rate (kg S^{-1}): This was determined as described by Mason and Hoseney (1986). Extrudates were collected as straight ropes up to 1 m long. Each rope corresponded to 10, 15, 20 or 30 sec running time. The ropes were weighed after 60 sec run on dry weight basis. Three determinations were carried out.

Specific mechanical energy (kW h^{-1}): This was evaluated according to Mason and Hoseney (1986). The ampere load and voltage of the extruder drive was used to calculate the watt-hours consumed. Together with the thorough put data, these values were used to calculate the specific mechanical energy (KW h^{-1}) through put as shown

$$\text{Specific mechanical energy} = \frac{\text{Amperes} \times \text{Volts/Kg/h}}{\text{thorough put}}$$

Where ampere is the extruder motor current. Volt is the extruder motor rating. kg h^{-1} through put = volumetric flow rate.

Residence time (sec): Residence time was determined during extrusion as reported by Iwe *et al.* (2001). A pint of red food grade colour was introduced at the feeding port and the time taken for the colour to first show-up at the die opening was recorded as the residence time. Three determinations were taken for each run.

Statistical analysis: All results were subjected to standard statistical analysis. Multiple regression analysis was used to fit the experimental data to the model.

The generalized regression model fitted was $Y = Bo+b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_nx^2 + b_{22}x_{22} + b_{33}x_{23} + b_{44}x_{24} + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{14}x_1x_4 + b_{23}x_2x_3 + b_{24}x_2x_4 + b_{34}x_3x_4 +$ - where Y = objective response, X_1 = feed composition, X_2 = feed mixture content, X_3 = extruder screw speed and X_4= extruder barrel temperature and $\acute{\varepsilon}$ = random error in which the linear, quadratic and interaction effects were involved. A computer programme SPSSWIN (11.0) SPSS INC. (2003), USA was used. The resulting models were tested for significance using analysis (ANOVA) and coefficient of determination (R^2). Significant terms were accepted at $p<0.05$ and in some critical cases at $p<0.1$ (Jin *et al.*, 1994; Howard, 1983). The R^2 of 0.6 was accepted for predictive purposes (Joglekar *et al.*, 1994). The terms that were not significant were deleted from the model equations.

For each significant model equation, response surfaces in three dimensional plots were generated on a computer programme STATISTICAL (STAT SOFT INC. USA) version 5.0 (1984-1995) by holding the two variables with the least and second least effects on the response constant (centre points) and changing the other two variables.

RESULTS AND DISCUSSION

Table 2: Estimated regression coefficients and ANOVA of torque

Regression on constants	Coefficients 643.38	Standard error 769.50	p-values	R^2
FMC	-6.28	29.32	0.360	0.50
SS	-2.23	4.80	0.738	
BT	-2.60	5.06	0.659	
FC*FC	1.36	5.55	0.111	
FMC*FMC	1.13	0.13	0.447	
SS*SS	-0.31	0.00	0.837	
BT*BT	-0.94	0.01	0.597	
FC*FMC	-1.46	0.00	0.183	
FC*SS	-1.60	4.52	0.147	
FC*BT	0.06	4.51	0.955	
FMC*SS	3.75	0.18	0.663	
FMC*BT	5.04	0.18	0.548	
SS*BT	2.06	0.03	0.796	
FMC*SS*BT	-3.11	0.00	0.751	
FC*FMC*SS*BT	1.67	1.20	0.150	
ANNOVA				
	DF	SS	MS	
Regression	15	5749.26716	383.28448	
Residual	20	5750.10386	287.50519	
F 1.3314	SIGN. F.2700			

Table 3: Estimated regression coefficients for specific mechanical energy

Regression on constants	Coefficients 45.19	Standard error	p-values	R^2
FMC	-7.56	1.63	0.28	0.50
SS	-7.22	0.27	0.29	
BT	-4.73	0.28	0.43	
FC*FC	-1.55	3.09	0.01	
FMC*FMC	0.61	0.01	0.69	
SS*SS	0.36	1.96	0.81	
BT*BT	0.83	2.83	0.65	
FC*FMC	0.91	1.51	0.41	
FC*SS	0.80	2.52	0.46	
FC*BT	0.74	2.51	0.50	
FMC*SS	10.02	0.01	0.26	
FMC*BT	6.25	0.01	0.47	
SS*BT	5.81	0.00	0.48	
FMC*SS*BT	-7.60	6.51	0.45	
FC*FMC*SS*BT	-1.02	6.66	0.30	
ANOVA				
	DF	SS	MS	
Regression	15	16.57753	1.10517	
Residual	20	17.79612	0.88981	
F 1.24203	SIGN. F.0.3201			

The results of the effect of Feed Composition (FC), Feed Moisture Content (FMC), Barrel Temperature (BT) and Screw Speed (SS) on extruder torque and specific mechanical energy are shown in Table 2 and 3, respectively. The results showed that none of the processing variables exerted significant ($p<0.05$) influence on these dependent extruder variables. Analysis of variance (Table 2 and 3) showed that there were no model significance ($p>0.05$) indicating that the model did not adequately fit the linear regressions. With average coefficient of determination, ($R^2 = 0.50$) the results were indicative that the model did not posess high predictive power and was therefore not used for predictive purposes. The result on torque values obtained from this study varied from 1.33-13 Nm. These values were not far from the values reported for extrusion of potato and soybean blends (Iwe *et al.*, 2001). Torque related to the power consumption of the extruder and about 98% of the power, input into the extruder is used for shearing and less than 1.5% is consumed in pumping. The results were in agreement with observed extruder trends that increase in FC (starch and protein) lead to increase in torque values (Bhattacharya and Prakash, 1994). Increase in SS has also been noted to increase shear and subsequent extruder internal temperature leading to increase in product flow and reduced residence time (VanLangriech, 1990; Mitchell and Areas, 1992). The decrease in torque is attributed to increased product flow at higher SS resulting in decreased residence time and hence less work for the extruder motor. This same trend was noted for the specific mechanical energy. Hulya (1996) showed that any variable that affects viscosity would correspondingly affect extruder torque and specific mechanical energy. Lowered values of torque and specific mechanical energy obtained in this work are attributable to the effect of addition of soybean flour. Though there are conflicting reports in literature, of effect of extrusion variables on torque and specific mechanical energy (Battacharya and Hanna, 1987; Weidman, 1990; Hulya, 1996) have reported similar results showing low values of torque and specific mechanical energy.

The results obtained for VFR in this study ranged from (7.28-189.76 kg h^{-1}) thorough input. The regression analysis (Table 4) indicated that none of the independent variables had significant ($p< 0.05$) effect on the volumetric flow rate. The analysis of variance however showed a significant ($p<0.05$) model fitness. Removing the non-significant terms the resulting polynomial equation became

$$VFR = -777.\ 087 + 0.962\ FC^2 - 1.023\ FCSS - 1.717\ BT^2 \quad (1)$$

The response surface generated for VFR, FC and SS is shown in Fig. 1. The surface showed that higher levels of soybean flour substitution and lower barrel temperatures resulted in decreased flow rate. Conversely higher temperatures and lower soybean percentage in the feedstock resulted in increased extrudate out put. The response surface plot of VFR, FC and BT is shown in Fig. 2. Like the effect of SS and FC, increase in BT with higher acha flour percentage encouraged increased extrudate flow while lower barrel temperatures with higher addition of soybean flour lowered extrudate output. Hulya (1996) had reported that higher SS avoured increased VFR by increasing extruder shear, raises extruder internal temperature and hence lowers the melt viscosity. This in turn increases VFR. The results of this study are in agreement with this report. The results indicated that soybean flour could be added up to 40% without lowering the VFR. BT showed a similar influence. Increased flow at higher temperature may be due to the increased lubricating effect of soybean lipids (Battacharya and Hanna, 1987).

The results showed that maximum VFR was obtained at 140 rpm 40% FC. The result of effect of processing variables on residence time of extrudates is presented in (Table 5). The results showed that the linear effects of Feed Moisture Content (FMC), Screw Speed (SS) and Barrel Temperature (BT) significantly ($p<0.05$) affected the residence time of extrudates.

Table 4: Estimated regression coefficients and ANOVA for volumetric flow rate

Regression on constants	Coefficients -777.09	Standard error	p-values	R^2
FMC	0.57	46.53	0.895	0.80
SS	2.513	7.62	0.553	
BT	2.41	8.03	0.519	
FC*FC	0.96	8.81	0.078	
FMC*FMC	-0.87	0.20	0.357	
SS*SS	-0.26	0.01	0.799	
BT*BT	-1.72	0.01	0.137	
FC*FMC	-0.09	0.00	0.899	
FC*SS	-1.02	7.18	0.142	
FC*BT	-0.05	7.18	0.944	
FMC*SS	-0.43	0.29	0.936	
FMC*BT	1.20	0.29	0.820	
SS*BT	-0.70	0.05	0.889	
FMC*SS*BT	-1.70	0.00	0.784	
FC*FMC*SS*BT	0.15	1.90	0.836	
ANOVA				
	DF	SS	MS	
Regression	15	57653.85009	3843.59001	
Residual	20	14486.98453	724.34923	
F 5.30627	SIGN.F.0.0004			

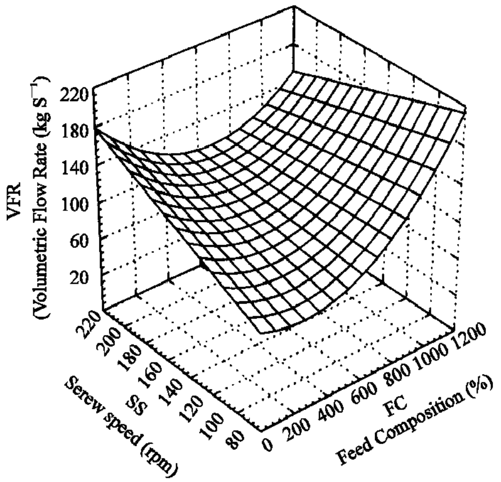

Fig. 1: Response surface plot of the effects of feed composition and screw speed on volumetric flow rate

Theresult of effect of processing variables on residence time of extrudates is presented in (Table 5). The results showed that the linear effects of Feed Moisture Content (FMC), Screw Speed (SS) and Barrel Temperature (BT) significantly ($p< 0.05$) affected the residence time of extrudates. Also the cross product effects of FC*SS, SS*BT and FM*BT significantly ($p<0.05$) affected the residence time. The quadratic effect of the FM^2 and SS^2,

Table 5: Estimated regression coefficients and ANOVA for residence time

Regression on constants	Coefficients -183.35	Standard error	p-values	R^2
FMC	9.38	4.03	0.054	0.80
SS	11.69	0.66	0.017	
BT	7.92	0.70	0.059	
FC*FC	-0.89	7.63	0.128	
FMC*FMC	4.123	0.02	0.0005	
SS*SS	1.39	4.85	0.179	
BT*BT	1.85	6.98	0.137	
FC*FMC	0.46	3.72	0.536	
FC*SS	-0.20	6.21	0.117	
FC*BT	1.17	6.21	0.005	
FMC*SS	-18.34	0.03	0.009	
FMC*BT	-16.20	0.03	0.008	
SS*BT	-15.72	0.00	0.008	
FMC*SS*BT	20.52	1.61	0.006	
FC*FMC*SS*BT	-0.34	1.64	0.66	
ANOVA				
	DF	SS	MS	
Regression	15	356.47247	23.7648	
Residual	20	108.49093	5.42455	
F 4.38098	SIGN.F.0.0013			

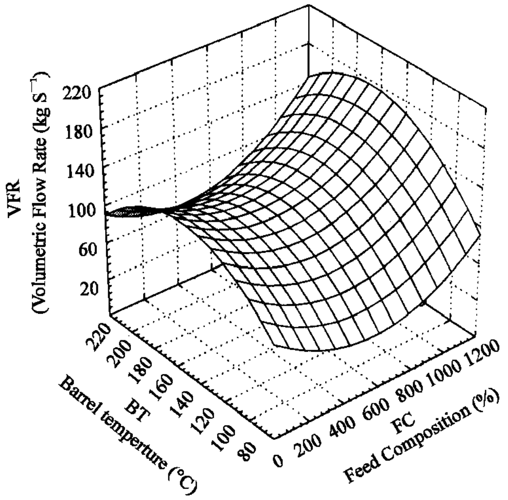

Fig. 2: Response surface plot of the effect of feed composition and barrel temperature on volumetric flow rate

however, exerted the greatest effect on residence time. The R^2 of 0.80 and the analysis of variance (Table 5) showed that there was significant ($p<0.05$), fitness of the model to the linear regression.

The model equation after elimination of non-significant terms became

$$\text{Rsed} = -188.348+4.123\ \text{FMC}^2 +1.17\text{FC*BT}20.52\ \text{FMC*SS*BT} -15.72\ \text{SS*BT}-16.203\ \text{FMC*BT}-18.34\text{FMC*SS} +11.69\text{SS} + 9.38\text{FMC}+7.915\text{BT} \qquad (2)$$

The response surface generated for, extrudate residence time with screw speed and feed moisture content is shown in Fig. 3. The surface indicated that increasing feed moisture content and screw speed led to increases in the residence time. In the same way increasing the feed moisture content and barrel temperature led to increase in residence time. The response surface plots of residence time and FM*BT and SS*BT are shown in Fig. 4 and 5, respectively. The plots showed a downward trend for the residence time with increase in these process parameters.

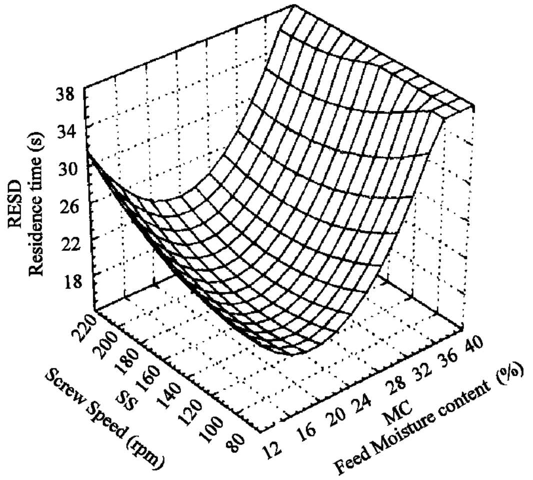

Fig. 3: Response surface plot of effect of screw speed and feed moisture content on extrudate residence time

Jager *et al.* (1992) observed that residence time was a function of at least the moisture content, feed rate, SS, barrel temperature and screw geometry. The result obtained from this work confirmed this observation. Results of this study showed that operating conditions for lower RESD were obtained at 24% FMC and 140 SS. Beyond these, residence time of acha/soybean blends may increase.

The relationship between these process variables (FMC and BT) and the dependent variable RESD was opposite. This was expected because decreasing the moisture content of the feed stock under decreasing extruder BT would lead to slower dough melt and more plugging of extruder die thus increasing the extrudate residency in the extruder barrel. These results were in agreement with the reports of Philip *et al.* (1984). Indications from the results obtained showed that moisture content exerted a greater effect on residence time than temperature.

The predictions of extrudate physical parameters using the developed models are shown in Table 6. The prediction of torque and specific mechanical energy were not considered because of lack of model significance. While the predicted residence time values were close approximations of the experimental values, there were

Table 6: Extrudate physical properties predicted using the developed model equations

	Torque		VFR		SME		Resd time	
Extru	Exp value	Pre value	Exp value	Pre value	Exp value	Pre value	Exp value	Pre value
1	7.00	ND	116.86	153.55	4.71	ND	16.67	19.82
2	7.00	,,	160.68	153.55	3.42	,,	17.24	19.82
3	7.00	,,	174.06	153.55	3.16	,,	23.13	19.82
4	4.00	,,	178.09	153.55	3.14	,,	17.94	19.82
5	2.50	,,	31.58	66.94	1.74	,,	29.36	24.60
6	3.00	,,	56.69	66.94	9.71	,,	19.18	24.60
7	7.00	,,	126.72	66.94	4.34	,,	19.18	24.60
8	9.33	,,	81.92	66.94	6.71	..	25.81	24.60
9	4.33	,,	147.05	153.55	3.74	,,	23.51	19.82
10	8.00	,,	134.61	153.55	4.09	,,	20.97	19.82
11	7.00	,,	189.76	153.55	2.89	,,	21.25	19.82
12	7.50	,,	154.15	153.55	3.57	,,	16.04	19.82
13	4.00	,,	70.40	66.94	7.83	,,	24.94	24.60
14	10.00	,,	137.07	66.94	4.01	,,	24.93	24.60
15	1.50	,,	10.00	66.94	55.00	,,	25.00	24.60
16	2.50	,,	15.00	66.94	3.67	,,	24.89	24.60
17	4.00	,,	151.02	114.57	3.64	,,	16.87	20.55
18	11.00	,,	85.49	114.57	6.34	,,	22.64	20.55
19	4.00	,,	174.46	183.86	3.15	,,	22.64	22.39
20	13.00	,,	17.28	10.65	9.60	,,	33.02	31.94
21	13.00	,,	100.58	114.57	5.47	,,	23.89	20.55
22	7.33	,,	117.72	114.57	4.92	,,	22.21	20.55
23	6.00	,,	68.94	114.57	7.98	,,	22.99	20.55
24	6.00	,,	98.36	114.57	5.59	,,	23.65	20.55
25	10.62	,,	136.21	114.57	4.04	,,	17.49	20.55
26	8.33	,,	127.72	114.57	4.30	,,	21.56	20.55
27	6.00	,,	112.45	114.57	4.89	,,	18.00	20.55
28	7.00	,,	114.76	114.57	4.90	,,	19.81	20.55
29	10.33	,,	106.36	114.57	5.17	,,	20.50	20.55
30	7.33	,,	118.34	114.57	4.65	,,	21.77	20.55
31	8.00	,,	121.84	114.57	5.52	,,	23.40	20.55
32	6.67	,,	109.67	114.57	5.01	,,	19.70	20.55
33	10.00	,,	133.60	114.57	4.12	,,	19.46	20.55
34	7.67	,,	101.25	114.57	5.43	,,	23.06	20.55
35	6.00	,,	127.78	114.57	4.31	,,	19.59	20.55
36	6.00	,,	112.45	114.57	4.89	,,	17.35	20.55

ND = Not determined because of low coefficient of determination (R^2)<0.60 and lack of model significance ($p<0.05$). Extr = Extrusion runs VFR = Volumetric Flow Rate SME = Specific Mechanical Energy Rsed = Residence time Exp = Experimental value Pre = Predicted value

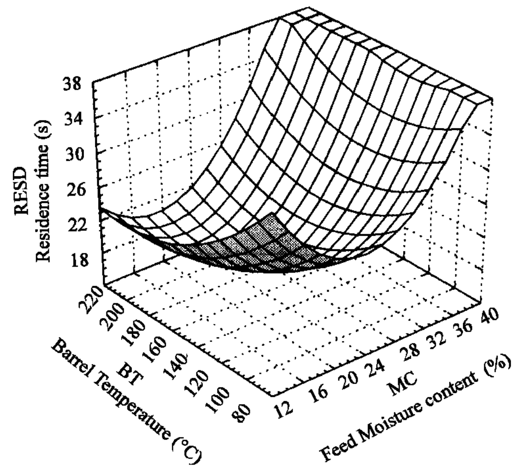

Fig. 4: Response surface plot of the effect of barrel temperature and feed moisture content on extrudate residence

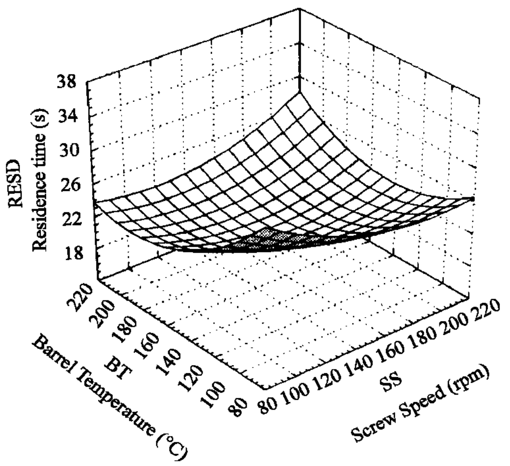

Fig. 5: Response surface plot of the effect of barrel temperature and screw speed on extrudate residence time

however, noticeable variations between the experimental values of volumetric flow rate and predicted values. This showed that there existed a more than quadratic relationship between the volumetric flow rate and the process variables. It might be that the second order polynomial was not adequate in predicting the dependence of extrudate torque and specific mechanical energy on the process variables.

Time content exerted a greater effect on residence time than temperature.

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