OPTIMIZATION OF HEAT AND MASS TRANSFER PROCESS IN SINGLE SCREW FLOATING FISH FEED EXTRUDER.

ABSTRACT

To optimize the extrusion conditions of locally developed single screw floating fish feed extruder. A factorial experiment in completely randomized design was employed to study the effect of extrusion variables: feed moisture content (20, 30, and 40 % wet basis), screw speed (158.5, 245, 334 rpm), die size (4, 6, 8, mm) while checking for their effect on Product temperature of the feed produced. Product temperature is strongly related to the extrusion process parameters under study. Product temperature decreased with increasing moisture content. Optimum condition was found at 74.11 °C at the feed section, 80.83 °C at compression section, and 85.15 °C at metering section, screw speed at 330.5 rpm, feed rate at 0.6 kg/min, die size at 7.47 mm, moisture content at 39.87 %, particle size at 1.1., and the R^2 coefficient for the final model is 0.93 which indicated that the model is good. The extruder was found to be cost efficient for floating fish feed production. Thus, model-fitting using response surface methodology was performed to examine their effect on product temperature. Quadratic coefficients fit the extrusion data very well, better than linear models. The equations relating the various dependent and independent variables were established to predict the performance of the machine.

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Keywords: Extrusion variables, product temperature, response surface methodology, model, fish feed.

1.0 Introduction

It is an established fact that protein from foods of animal origin is lacking in every day diet of many Nigerians (Olayide *et al.,* 1972). This deficiency is responsible for a great deal of ill-health and many deaths in almost all the states of Nigeria. Even in the absence of ill-health, protein deficiency leads to poor growth, muscular weakness and an increased susceptibility to many diseases (Das *et al*., 1996). The support to meet the demand by various domestic animals and fish from natural water has so far failed to provide the populace with balanced diet needed. It is imperative therefore to increase protein production by all possible means. The first is by the intensification of existing means of production and secondly, by the introduction and development of additional sources of protein. Fish culture in artificial water is one of the best ways to increase the availability of food rich in protein (Das *et al.*, 1996).

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Fish are known to contain important constituents for the human diet such as nutritional and readily-digestive proteins, lipid-soluble vitamins, micro elements and polyunsaturated fatty acids (Shah mohammad, *et al*., 2016). Development of fish feed technology in aquaculture sector is very low particularly in Africa and other developing countries of the world (FAO, 2003). Feed as one of the major inputs in aquaculture production is facing fundamental challenges of development leading to poor growth of aquaculture in the African continent (Fayose et al., 2012).

Development and management of fish feed, play a very vital role in aquaculture growth and expansion and also it is a major factor that determines the profitability of aquaculture venture (Gabriel *et al*., 2007). Many other studies have reported effects of different process variables and extruder configuration on properties of different blends of extrudates (Liu *et al*.,2011).

To overcome extrusion problems many variables such as feed composition, feed rate (FR), barrel temperature, screw speed (SS), screw configuration and the die geometry should be controlled (Meng et al., 2009). The combination parameters of feed rate and screw speed are important, since they determine the filling level in the extruder. This is critical to the process because it governs the balance between the weak and strong mass transfer mode which influences the shear stress and resistance time (Chokshi et al., 2004).

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2.0 Materials and Methods

Materials

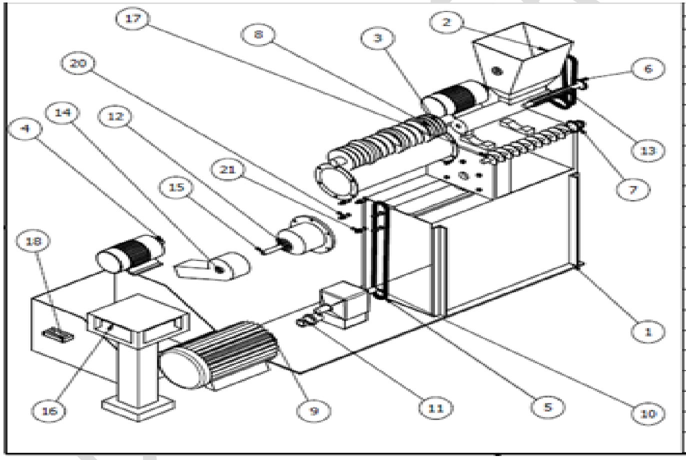
Cassava tubers (Manihot esculenta Crantz) TMS 30572, were sourced from experimental plots at the Federal College of Agriculture, Akure and processed into flour. The materials were passed through a 300um sieve and moisture contents of sample was determined as described by AOAC (1995) approved method. The feed materials used for the experiment were procured at various mills in Akure, Ondo state and Cossy fish integrated in Kainji, Niger state. The materials were prepared and processed by the standard recommended by Nigerian Institute for Oceanography and Marine Research (NIOMR) approved method. The percentage of samples recipes for the experiment is as follows: Cassava 39 %, Soy meal 20 %, Groundnut 20 %, Fish meal 20 %, Fish premix 0.5 %, Nitox antimould 0.5 %. Temperature data logger was design and fabricated at the Electronics workshop of the Physics Department Federal University of Technology Akure, Nigeria.

Sample Preparation

The materials used include cassava flour, soya bean meal, fish meal, vitamin premix, lysine pigments, methionine, oyster shell, bone meal, industrial yeast etc. The feed materials were finely ground and weighed to derive the required proportions (IITA, 2005). Each material for the formulation to be tested was blended thoroughly by mixing manually. The protein content values used were obtained from NAERLS (2002).

3.0 Extrusion

The extruder used in this study is a dry type made up of three (3) main units namely the feeding unit, the compression and melting unit all fabricated using locally available materials. The extruder was developed at the Agricultural Engineering Department, Federal University of Technology Akure, Nigeria. The Extruder consists of a steel barrel which houses the extrusion worm equipped with hopper which is the feeding unit at one end and a die plate where the extrusion takes place at the other end of the barrel, as shown in Figure 1. The machine is powered by a 30hp, 3-phase electric motor in which the power transmission is accomplished through chains and sprockets. Seven vents are located at the three main units of the extrusion barrel through which extrusion temperature was monitored during the experiment. Figure 1 shows the isometric view of the extruder.



PARTS LIST		
ITEM	DESCRIPTION	QTY
21	Hexagon nuts	11
20	Plain washers -	11
19	Hexagon head bolt	11
18	Collection Container	1
17	Feeder Screw	1
16	Motor support	1
15	Cutter	1
14	Outlet Channel	1
13	Spike Shaft	1
12	Die	1
11	Coupling	1
10	Speed Reduction Gear	1
9	Motor 1	1
8	Barrel screw	1
7	Sprocket 2	3
6	Sprocket 1	3
5	Chain 1	3
4	Motor 2	2
3	Barrel	1
2	Hopper	1
1	Main frame	1

Figure.1: shows the isometric view of the extruder.

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4.0 Experimental Procedure

The machine was run to stabilization with 1-3kg of feed materials for about 20 minutes before experiment started. The pre-conditioned feed materials were fed into the extruder at 6Kg/h. The feeding section of the extruder was maintained at room temperature. The extrusion parameters varied were the extruder speed, moisture content, die size and particle size. The extrudates discharged were cut automatically with cutting blade to lengths proportional to the expanded die diameter. Product temperatures were varied by continuous running of the machine, thereby building up the temperature. A major reason why heat is better generated through viscous dissipation than that added or removed through the barrel walls is that heat generated by drive unit (through viscous dissipation) is more dominant and cost efficient (Liang *et al*., 2002). Extrudates produced were oven dried at 60 ºC for periods of 30, 60 and 90 minutes respectively in order to bring them all to the required feed moisture content of about 10-12 % wet basis.

5.0 Experimental Design

Data analysis was done by using Microsoft excel 2010 for graphical interpretation of the results. The independent variables and their variation levels considered in this study were die size (4 mm, 6 mm, 8 mm) Feed rate (0.4 kg/min, 0.60 kg/min, 0.79 kg/min) Screw speed (158.5 rpm, 245 rpm, 335 rpm) Moisture Content (20 %, 30 %, 40 %) and Particle size (0.5 mm, 0.7 mm, 1.1 mm). Response surface Methodology (RSM), a Mat lab 2014 a tool was used to optimize the effect of heat and mass transfer process on the fish feed extruder. Box-Behnken design (BBD), a tool in Design- Expert was used in the optimization of process variables with five factors at three levels with 24 runs, including 5 central points .The responses function was partitioned into linear, quadratic, and interactive components. Experimental data were fitted to the second-order regression equation, as shown in the following equation:

$$y= \beta o +\beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} x_{11} + \beta_{22} x_{22} + \beta_{33} x_{33} + \beta_{12}\ x_{12} + \beta_{13} x_{13} + \beta_{23}\ x_{23} \quad \ldots\ldots\ldots\ldots.. \quad (1)$$

The equation was established to fit the experimental data for each response (γ_1), where the x_1, x_2, $x_3$were barrel temperature in the three zones (^{0}C), Feed Rate (H_z) and Screw Speed (H_z) respectively. β_1, β_2, β_3, β_{11}, β_{22}, β_{33}, β_{12}, β_{13}, and β_{23} were the regression coefficients to be determined. The experimental design and statistical analyses were performed using Design-Expert software (Version 8.0.7.1, Stat Ease Inc., Minneapolis, MN, USA). The model adequacies were checked in terms of the values adjusted. Analysis of variance (ANOVA) was carried out using Microsoft Excel to determine the significance of the models. Verification of optimized conditions and predicted values were done in triplicate to confirm the validity of the models.

6.0 RESULTS AND DISCUSSIONS

Effect of Extrusion Speed on Product Temperature

The extrusion speed had a great effect on product temperature for the evaluated sections of feed, compression and metering respectively. This show that product temperature required to get materials extruded increases with speed. At 158.5rpm speed, the product temperature for the three evaluated sections were 76.34 ^{0}C, 83.55 ^{0}C, and 91.68 ^{0}C while at 245 rpm speed, the product temperature at the three sections were 73.09 ^{0}C, 95.36 ^{0}C, and 116.36 ^{0}C. At 334 rpm speed, product temperature values were 76.52 ^{0}C, 86.76 ^{0}C, and 95.98 ^{0}C. The product temperature increased along the barrel, the decreased in product temperature as the speed increased to 334 rpm is best explained by the increase in material transfer or flow rate per time relative to the extruder screw pitch which was constant. However, the materials stayed longer in the barrel at lower speed, experimental observation showed that the materials almost fully dried, non gelatinization before ejection from the machine thus affect other properties as well as pellet forming ability of the materials. The highest product temperature values were obtained at 245 rpm speed which thus leads to a conclusion that the best speed for the extruder is 245 rpm speed.

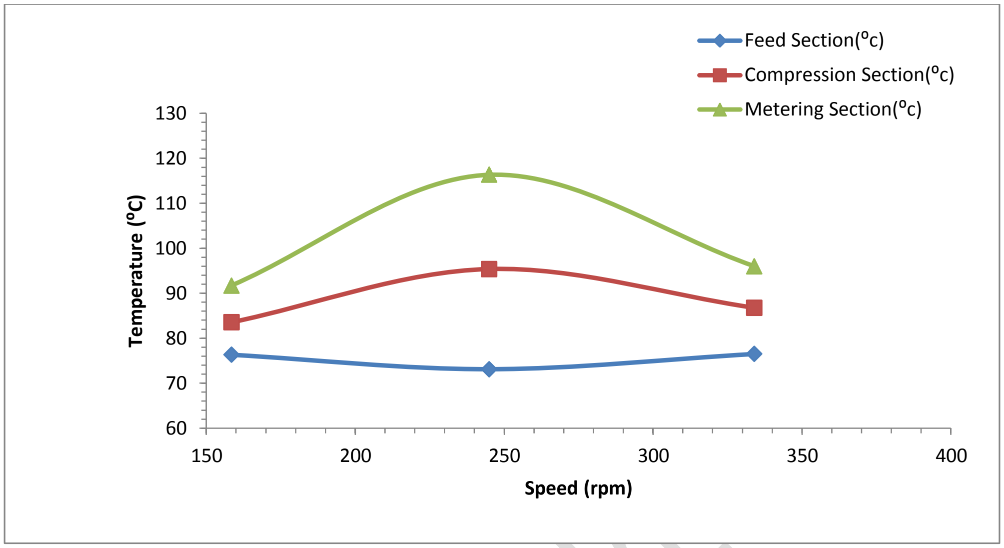

Figure 2: Variation of Extrusion Speed with Product Temperature

Effect of Extruder Feed Rate on Product Temperature

The feed rate had a definite effect on the product temperature in the extrusion process as the extent of materials in the barrel determined how long the barrel temperature had influence on the materials before exiting the extruder. Figure 3, shows the value of product temperature at the three sections on the barrel. At 0.41 kg/Min, the product temperature values were 74.06 ^{0}C, 82.75 ^{0}C, and 90.78 ^{0}C. At 0.60 kg/min there were decreased in product temperature values, 70.75 ^{0}C, 77.7 ^{0}C, and 86.25 ^{0}C. The product temperature values further decreased at 0.79 kg/min to 68.5 ^{0}C, 74.78 ^{0}C, and 86.07 ^{0}C. The feed rate highly affects mass flow of materials during extrusion. However, the highest product temperature values were obtained at 0.41 kg/min depending on other factors involved.

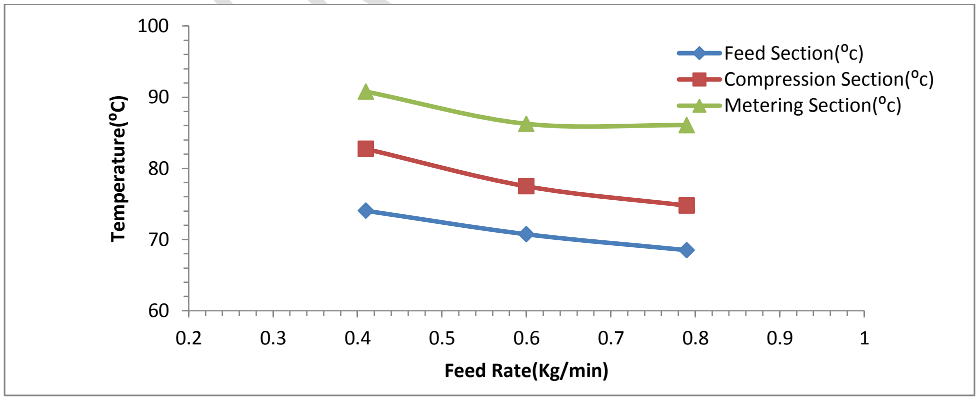

Figure 3: Variation of Extrusion Feed Rate with Product Temperature

Effect of Die Size on Product Temperature

From Figure 4, product temperature in the extruder was on a general note affected by the die size. It was here observed that retention time require for 4 mm die size extrusion was higher than that of 6 mm and 8 mm die size which is attributed to increased flow rate as the exit surface area increased but irrespective of the time differences, retention time was enough to attain required level of gelatinization. The lowest product temperature of 103.5 ^{0}C were obtained at 8 mm die size while 6 mm die size had product temperature of 105.07 ^{0}C and 4 mm die size had the highest product temperature of 109.25 ^{0}C. The differences experienced in the product temperature can be attributed to increased flow rate as the exit surface area and the materials composition could have affected the product temperature such as flow of the materials inside the extruder barrel as well as response of such materials to temperature and shear as a result of friction between barrel wall and extruder screw. However, 4 mm die size has the highest product temperature of 109.25 ^{0}C.

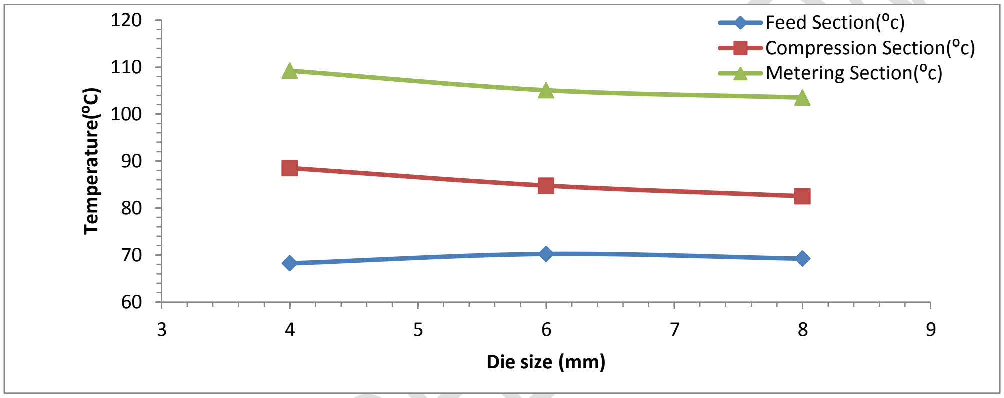

Figure 4: Variation of Extrusion Die Size with Product Temperature

Effect of Moisture Content on Product Temperature

The effect of moisture content on product temperature of extrudates produced from extruder. Observations from the results show that the lowest product temperature was obtained at 40 % moisture content. However, increment in product temperature was observed for the 20 % to 30 % moisture content. Therefore, highest product temperature was recorded at 30 % moisture content.

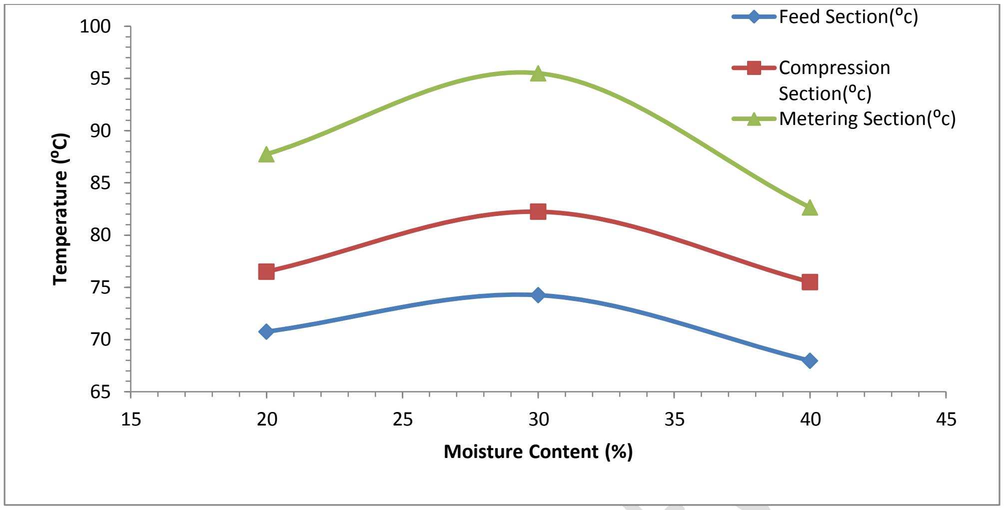

Figure 5: Variation of Extrusion Moisture Content on Product Temperature

Effect of Particle Size on Product Temperature

Particle size of feed ingredients for floating fish feed is an important variable when manufacturing aqua-feeds. The effect of particle size on product temperature are shown in Figure 6, for fine particle (0.5 mm), medium particle (0.7 mm) and coarse particle (1.1 mm) it was observed that the lowest product temperature were obtained at 1.1 mm particle size while fine particle size (0.5 mm) had highest product temperature values at the three section of the barrel which thus leads to a conclusion that the best particle size is 0.5 mm (fine particle).

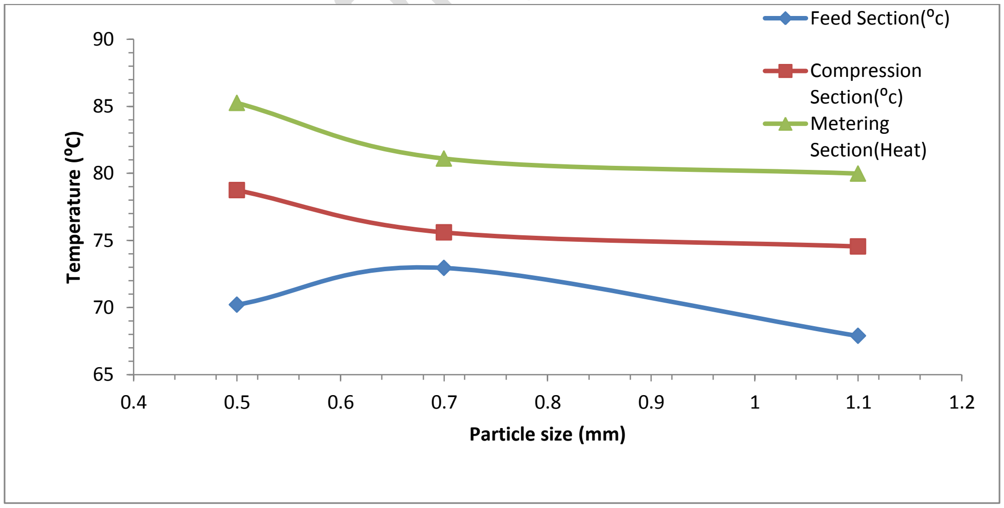

Figure 6: Variation of Particle Size on Product Temperature.

7.0 Statistical Analysis for Selected Models

The analysis of variance (ANOVA) for the selected quadratic polynomial model for heat and mass transfer from the feeding, conversion and metering sections was listed in Table 1. Lack-of-Fit is the variation due to the model inadequacy. The lack of fit was not significant for both models. Therefore, there is no evidence to indicate that the models do not adequately explain the variation in the responses. It also showed that, for heat and mass transfer of the extrudates in the extruder, the speed and moisture content have important role in determining heat and mass flow. Because both of the variables played more prominent role in the extruder efficiency for producing a floating fish feed, by increasing speed and moisture content, the extrudates quality content increases significantly. By heating, it gives energy to the molecules in the system to vibrate thus weakening the bond between compounds, disrupting cell membrane, and causing the compound in the materials to mix very well. The Model F-value of 0.04 implies the model is significant relative to the operation and process parameters. There is a 4 % chance that an F-value this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case there are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. The "Lack of Fit F-value" of 0.67 implies the Lack of Fit is not significant relative to the pure error. There is a 65.46 % chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good.

Table 1: Summary of analysis of variance (ANOVA) for Response Surface Quadratic Model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	1672.84	20	83.64	2.09	0.040	Significant
A-SPEED	*78.64*	*1*	*78.64*	*1.97*	*0.2554*	Significant
B-FEED RATE	*81.70*	*1*	*81.70*	*2.04*	*0.2483*	
C-DIE SIZE	*242.63*	*1*	*242.63*	*6.07*	*0.0906*	
D-MOISTURE CONTENT	*34.34*	*1*	*34.34*	*0.86*	*0.4225*	Significant
E-PARTICLE SIZE	*0.023*	*1*	*0.023*	*5.727E-004*	*0.9824*	
AB	*22.96*	*1*	*22.96*	*0.57*	*0.5038*	
AC	*2.84*	*1*	*2.84*	*0.071*	*0.8073*	
AD	*28.07*	*1*	*28.07*	*0.70*	*0.4637*	
AE	*15.79*	*1*	*15.79*	*0.39*	*0.5744*	
BC	*7.76*	*1*	*7.76*	*0.19*	*0.6894*	
BD	*62.02*	*1*	*62.02*	*1.55*	*0.3014*	
BE	*99.03*	*1*	*99.03*	*2.48*	*0.2137*	
CD	*358.99*	*1*	*358.99*	*8.98*	*0.0579*	
CE	*216.50*	*1*	*216.50*	*5.41*	*0.1025*	
DE	*142.53*	*1*	*142.53*	*3.56*	*0.1555*	
A^2	*14.87*	*1*	*14.87*	*0.37*	*0.5852*	
B^2	*5.49*	*1*	*5.49*	*0.14*	*0.7357*	
C^2	*5.10*	*1*	*5.10*	*0.13*	*0.7447*	
D^2	*2.95*	*1*	*2.95*	*0.074*	*0.8035*	

E^2		*26.33*	*1*	*26.33*	*0.66*	*0.4765*	
Residual		119.99	3	40.00			
	Lack of Fit	*68.58*	*2*	*34.29*	*0.67*	*0.6546*	*not significant*
	Pure Error	*51.41*	*1*	*51.41*			
Cor Total		1792.83	23				

The ANOVA of quadratic regression model demonstrated that both models were highly significant, evident from Fisher’s -test with high value and low value as shown in Table 2.

Table 2: The Regression Equation Coefficients for the Predictive Model for Heat and Mass Transfer of the Extruder

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	83.55	1	4.06	70.64	96.46	
A-SPEED	-2.39	1	1.70	-7.80	3.03	1.15
B-FEED RATE	2.36	1	1.65	-2.89	7.61	1.21
C-DIE SIZE	4.22	1	1.71	-1.23	9.68	1.22
D-MOISTURE CONTENT	1.63	1	1.76	-3.97	7.24	1.21
E-PARTICLE SIZE	-0.041	1	1.70	-5.45	5.36	1.20
AB	-1.51	1	1.99	-7.85	4.83	1.21
AC	-0.54	1	2.03	-7.01	5.93	1.25
AD	1.89	1	2.25	-5.28	9.05	1.39
AE	-1.27	1	2.02	-7.69	5.15	1.19
BC	-0.85	1	1.93	-7.01	5.30	1.26
BD	-2.48	1	1.99	-8.82	3.86	1.18
BE	-3.05	1	1.94	-9.23	3.12	1.23
CD	6.02	1	2.01	-0.37	12.42	1.18
CE	-4.56	1	1.96	-10.80	1.68	1.23
DE	-3.88	1	2.05	-10.42	2.66	1.28
A^2	2.38	1	3.91	-10.05	14.82	1.48
B^2	1.46	1	3.95	-11.11	14.03	1.25
C^2	-1.46	1	4.09	-14.47	11.55	1.64
D^2	1.01	1	3.71	-10.81	12.83	1.51
E^2	3.21	1	3.96	-9.39	15.82	1.49

8.0 Response surface optimization of extrusion parameters

The RSM was used to optimize the heat and mass transfer process in single screw floating fish feed extruder. The operating parameters (die size, feed rate, and screw speed) were served as the variables and process parameters (moisture content and particle size) were served as the response. The design matrix of the variables in the uncoded units and the response data of the RSM experiment are shown in Table 2. By employing multiple regression analysis, the predicted response Y can be obtained by using the following second-order polynomial equation:

Y = 83.55 – 2.39*A + 2.36*B + 4.22*C + 1.63*D -0.041*E – 1.51*AB – 0.54*AC + 1.89*AD – 1.27*AE – 0.85*BC – 2.48*BD – 3.05*BE + 6.02*CD – 4.56*CE – 3.88*DE + 2.38*A^2 + 1.46*B^2 – 1.46*C^2 + 1.01*D^2 + 3.21*E^2. …………………………. (2)

Where Y is predictive, X_1 is the screw speed (rpm), X_2 is the feed rate (H_z), and X_3 is the die size (mm). The statistical significance of the regression equation checked by the F-test, the big f value (2.09) and the small probability value ($P > 0.40$) indicated high significance of the obtained model. Mean while, the lack-of-fit F value of 0.67 and P value of 0.6546 implied that the lack-of-fit was not significant related to the pure error, the coefficient of variation of 7.18 % indicated that the obtained model was highly reproducible. The significance of each coefficient was determined using the F value and P value. The bigger the F value and the smaller the P value, the more significant the corresponding coefficients. It was concluded that the linear, 2FI, quadratic and cubic were significant with small P value ($P < 0.05$). The other term coefficients were not significant ($P > 0.05$). Among the three observed variables Screw-speed, presented the highest F value, which indicated that Screw speed was the most dominant factor in deciding the response. The product temperature in the resulting extrudates was affected by screw speed, moisture content and particle size. Screw speed (A) displayed a quadratic effect on the response and peaked at 330.5 rpm. This finding could be explained by the fact that the increase in screw speed tends to increase shearing force but shorten the transit time of the feed across the barrel. The product temperature increased with feed moisture content, the product temperature reached its peak at moisture content of 30 %, followed by a decline with further increase in feed moisture content.

9.0 Verification of Optimized Condition and Predictive Model

In order to optimize the extrusion conditions, both graphical and numerical multiple optimization procedure were carried out. As shown in Figure 7. Three-dimensional (3D) response surface plot were drawn for better visualization of the final reduced model for graphical optimization procedure. As for numerical multiple optimizations, response optimizer was used to determine an optimum set level of independent variables that jointly optimized a set of responses by satisfying the requirements for each response are shown in Table 3.

Table 3: Optimum Parameters

Parameters	**Numerical Variables**
Product Temperature (^{0}C)	
Feed Section	**=74.11**
Compression section	**= 80.84**
Metering Section	**= 85.16**
Screw Speed (rpm)	**=330.51**
Feed Rate (Kg/hr)	**=0.6**
Die Size (mm)	**=7.47**
Moisture Content (%b)	**=39.88**
Particle Size (mm)	**=1.1**
Desirability	**= 0.711**

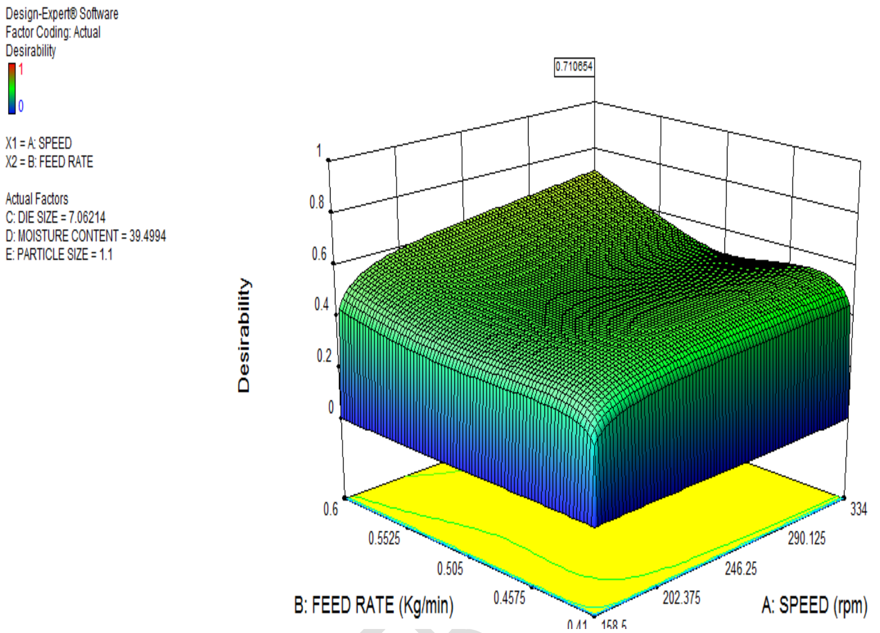

Figure 7: Surface response Optimization of effect of heat and mass transfer process in a single screw floating fish feed extruder.

10 Validation of the Model

In order to verify the adequacy of final reduced models, two sample t-test and one sample t-test were carried out to compare the experimental and predicted values for theoretical and practical validation procedures at optimum point respectively. Close agreement and no significant difference between the experimental and predicted values were needed for validation of the final model.

11. CONCLUSION

The product temperature response of a locally developed single screw extruder has being well characterized. Both linear and quadratic coefficients fit the data very well. However, the quadratic fits generated by the response surface regression analysis have better fit than the linear one by stepwise regression analysis. Based on this work, it could be concluded that the factors affecting the extrusion process are all interrelated and it might be difficult to discuss each factor independent of the other. Generally, the study revealed that it is better to fix the extrusion variables at a moderate values to enhance product temperature.

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