Effect of Particle Size and Moisture Content on Viscosity of Fish Feed

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ABSTRACT

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A model was developed for the influence of particle size on the extrusion of a fish feed and the physical characteristics of the extrudates evaluated. The study was conducted using factorial experiments in a fractional replication design for four variables with three levels, and one-third of the replicates (3^4 factorial in 27 units) were examined in a laboratory extruder. The torque-screw speed measurement was used to develop a viscosity model equation that considered different shear rates, product temperature, initial moisture content, and particle size. When particle size decreased, the apparent viscosity became smaller. The barrel pressure was important in producing extrudate with a uniform volume over the range of processing conditions tested because it had a strong correlation with the volumetric expansion. The material with lower moisture and larger particles caused the specific mechanical energy to increase. The viscosity model developed in this study can be applied to the development of large-scale extrusion models that determine the effect of particle size on the feed material extrudates.

Food and feed extrusion cooking is a unit operation in which various biological products are produced using cereal, oilseed, or other water and carbohydrate mixtures. Fish feed is one example of these extruded products. Under high-temperature-short-time (HTST) cooking, an extruder mixes, shears, and forces materials through a restriction (or die) that is designed to form or puff-dry the materials (Rossen and Miller 1973; Harper 1981). These cooking, mixing, shearing, and compressing processes are related strongly to the rheological properties of the materials in the extruder.

Because all materials have distinct rheological properties, an understanding of rheology and momentum transfer in an extruder can optimize development of food products, processing methods, scale-up of new processes, process control, and product quality. Apparent viscosity (hereafter referred to as viscosity) is one of the most important rheological properties of non-Newtonian biological materials. Meuser et al (1987) suggested that viscosity (or shear stress) can be used as a variable for continuous on-line control. After viscosity is found, momentum and heat transfer analysis for extrusion can be studied further. However, the rheological properties of feed materials during extrusion and the engineering analysis for feed extrusion seldom have been discussed in the literature.

One way to obtain viscosity is to use a well-defined viscosity model equation. A simple and good mathematical expression of viscosity can represent the mean of a large quantity of rheological data. The modeling equation can be in many forms, but no single master model can represent and explain all situations (Bhattacharya and Hanna 1986; Steffe 1996). Three criteria to select a particular rheological equation are how well it represents the experimental data, how well it predicts phenomena controlled by the viscosity, and how convenient it is to use (Clark 1978).

Since Harper et al (1971) presented a viscosity model equation for biological materials in an extruder (Equation 1), several researchers (Remsen and Clark 1978; Chen et al 1978; Bhattacharya and Hanna 1986; Morgan et al 1989; Mackey and Ofoli 1990; Kokini et al 1992 a,b) have developed empirical viscosity models for cereal dough in an extruder, based on the equation

$$\eta = m\dot{\gamma}^{(n-1)} \exp\left[\frac{\Delta E}{RT} + B_2 MC\right] \tag{1}$$

where η is the apparent viscosity (N s/m^2), m is the consistency coefficient (N s^n/m^2), $\dot{\gamma}$ is the shear rate (sec), n is the flow behavior index (dimensionless), ΔE is the activation energy of the material [J (g-mol)$^{-1}$], R is the gas constant (8.314 J(g-mol-K)$^{-1}$), T is the product temperature (K), B_2 is a constant for moisture content (%$^{-1}$), and MC is the moisture content of the material (%, wb).

The previous researchers, however, mainly focused on the effects of shear rate, temperature, moisture content, time-temperature history, strain history, and starch gelatinization on viscosity. Not many models show the effect of particle size on viscosity, although the influence of particle size on the extrudate has been recognized (Mohamed 1990; Garber et al 1995; Jamin and Flores 1998). Additionally, the particle size distribution of feed materials affects the quality of feed whether it is extruded or steam pelleted (Reece et al 1986).

The objectives of this study were to 1) develop a viscosity model with particle size consideration for non-Newtonian biological materials (e.g., fish feed) during extrusion, and 2) determine the effects of particle size, initial moisture content, product temperature, and screw speed on expansion and momentum transfer parameters. These parameters included viscosity, torque, absolute pressure at the end of the barrel (hereafter referred to as barrel pressure), mass flow rate in the extruder, and specific mechanical energy (SME).

MATERIALS AND METHODS

Experimental Design

By using factorial experiments in a fractional replication design for four variables with three levels, one-third of the replicates (3^4 factorial in 27 units) were examined (Cochran and Cox 1992). The four independent variables were temperature profile of the extruder wall, initial moisture content of the fixed fish feed formula (hereafter referred to as feed mix), geometric mean particle diameter (d_{ps}, mm) of the feed mix, and screw speed of the extruder. Three levels for each variable were studied (Table I) for a total of 27 treatments. Each treatment was duplicated.

The statistical analysis was performed with the Statistical Analysis System (release 6.08 for Windows, SAS Institute, Cary, NC). Appropriate significance effects of the factor means on the dependent variables were determined when the P values of the factors were compared at the 0.05 and 0.01 significance levels (Type III error analysis). The analysis of linear correlation and the coefficient of determination were performed with Microsoft Excel software (v. 5.0a). Multiple regression analysis (SAS) was used to determine the parameters of the viscosity equations. Second-order polynomial regression equations were generated using the RSREG and GLM procedures (SAS), and response surface plots were produced using the S-Plus program (v. 3-4 for UNIX, Mathsoft, Seattle, WA).

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Extruder

During the entire experiment, a single-screw extruder (C.W. Brabender 2003) with a 3:1 compression ratio and a 20:1 screw length to diameter, was run at 40, 70, and 100 rpm (Type 2003GR-8, Volt 230, Amp. 12). Because product temperature is the main factor that affects viscosity in an extruder, the product temperature at the end of the barrel (hereafter referred to as product temperature) was preferred for studying the thermal effect on viscosity. The product temperature was indicated by a temperature probe inserted in the product before entering the extruder die. The three measured product temperatures were 372.6 ± 0.8, 385.6 ± 0.5, and 397.6 ± 0.5 K for the extruder wall temperature profiles of 95–105–115°C, 110–120–130°C, and 125–135–145°C, respectively. A one circular hole die (3.17 mm diameter) was used in this study.

Raw Materials

The fish feed mix used in this study consisted of 32% soybean meal, 21.4% yellow dent corn, 20% corn gluten meal, 10% fish meal, 7.5% dried distiller solubles, 5% whole wheat, 2% animal tallow, 1% dicalcium phosphate, 0.5% trace mineralized salt, 0.5% vitamin premix, and 0.1% choline chloride (Lam 1996). Because this experiment focused on three levels of particle size, additional milling was required. The ingredients in the feed formula were mixed using a laboratory batch mixer (model B2224-1, Rapids Machinery, Marion, IA). One-third of the total of the feed mix was ground using a Fitz mill (model D, The Fitzpatrick Co., Elmhurst, IL) with an 8-mesh screen, and another third of the feed mix was ground using a flour mill (Magic Mill III, Salt Lake City, UT). The particle size distribution of the fish feed mix was determined using the ASAE Standard S319.1 (1989). Because the smaller particles ($d_{ps} < 0.21$ mm) were too sticky to pass through the screen, a 2% dispersion agent (Zeofree 80, J. M. Huber Corp., Quincy, IL) was added to improve the flowability of the particles through the screens. The particle size test for each material studied (Table I) was repeated three times.

The three materials were conditioned separately to the three desired moisture contents (Table I) in a rotational parabola bowl (Dayton Electric, Chicago, IL), while water was sprayed into the rotating bowl at 90 rpm for 20 min. After grinding and conditioning, nine different treatments (three particle size ranges × three moisture contents) were created. Each of the conditioned treatments was transferred to a polyethylene bag and was kept overnight at 5°C to equilibrate the moisture within the sample. Before extrusion, each conditioned treatment was removed from the cooler in advance to reach room temperature (25 ± 2°C) and to determine its moisture content before extrusion. Moisture content was determined using the Method 44-15A (AACC 2000), repeated three times, and the results were averaged.

TABLE I
Experimental Levels of Independent Variables

Independent Variable	1	2	3
Extruder wall temp. profile (°C)[a]	95-105-115	110-120-130	125-135-145
Fish feed mix moisture content (%, wb)	21.57 ± 0.38	26.36 ± 0.70	33.88 ± 0.58
Geometric mean diameter (mm)	0.212 ± 0.013	0.370 ± 0.026	0.477 ± 0.006
Screw speed (rpm)	39.57 ± 0.20	70.00 ± 0.26	99.91 ± 0.02

[a] Feeding zone-metering zone-die zone.

TABLE II
Coefficients for the Viscosity Equation (Equation 7)

Equation Parameters	Parameter Estimate	Standard Error	T for H_0 Parameter = 0	Prob > |T|
ln(m)	9.2597	1.3565	6.822	0.0001
(n – 1)	–0.7538	0.09113	–8.373	0.0001
$\Delta E/R$	1,624.22	497.725	3.263	0.0020
B_2	–0.1220	0.00678	–18.000	0.0001
B_3[a]	–0.0075	0.00077	–9.638	0.0001

[a] $b'_3 = (B_3\pi)/6$.

Mechanical and Physical Parameters

Torque, screw speed, barrel pressure, and product temperatures were recorded every 10 sec using a data acquisition system (data processing Plasti-Corder PL 2000, C. W. Brabender), after the extruder was working under steady-state conditions. The values of torque, screw speed, barrel pressure, and product temperature at the end of the barrel for each treatment were averaged from 12 values. The product temperature at the end of the die was computed by averaging six values. The initial temperature of the raw material was recorded by a thermometer (model H-08528-10, Digi-Sense, Cole-Paramer Instrument, Niles, IL). Two repetitions were made for the initial temperature.

A timer was used to measure the time for the fish feed to go through the extruder after steady-state conditions were established, using a fish feed mix dyed with food colorant to identify each repetition. For each repetition, the extrudate was collected and weighed. For each treatment, eight repetitions of the mass flow rate of extrudate were obtained but only the five closer measurements were used to calculate the average value of mass output rate for each treatment. The mass flow rate of the dough in the extruder was calculated

$$m_d = m_e\frac{(1-MC_e)}{(1-MC_d)} \qquad (2)$$

where m_d is the mass flow rate of dough (mass throughput, g/sec), m_e is the mass flow rate of the extrudate (mass output flow rate, g/sec), MC_e is the moisture content of extrudate (extruded fish feed, decimal, wb), and MC_d is the moisture content of dough (raw material, decimal, wb). The mass output feed rate was 0.61 ± 0.18, 1.06 ± 0.31, and 1.46 ± 0.41 g/sec for the 40, 70, and 100 rpm, respectively.

The specific mechanical energy transferred to the extrudate is a function of torque, screw speed, and mass flow rate, as shown by Equation 3 (Meuser and van Lengerich 1984a,b; Abecassis et al 1994; Kokini et al 1992a,b)

$$SME = \frac{Tor\left[\frac{2\pi}{60}\right]N_{sc}}{m_d\left[\frac{3600}{1000}\right]} \qquad (3)$$

where SME is the specific mechanical energy (W-hr k/g, wb), Tor is the torque (N m), and N_{sc} is the screw speed (rpm).

Bulk Density and Expansion Indexes

The dimensions of the extruded feed were measured using a digital micrometer (model 293-725-30, Mitutoyo, Japan) and the weight was determined with an analytical balance (single-range model A-250, Denver Instrument, Arvada, CO). The micrometer and the balance were connected to a personal computer equipped with a data acquisition system. Each sample was measured at three different radial sections for the diameter and at two different sections for the length. Nine repeated measurements of extrudates were made for each treatment. The bulk density of the fish feed was calculated as the weight over the volume (pelleted fish feed was assumed to have a

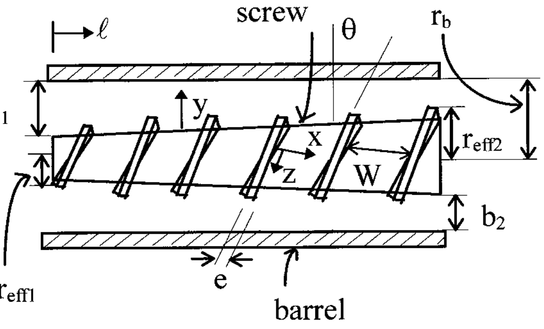

Fig. 1. Schematic diagram of a single-tapered screw.

cylinder shape). For product diameter, a total of 36 repetitions (3 × 12) were made. The cross-expansion ratio (CSEI) was calculated by dividing the square of the extrudate radius by the square of the die nozzle radius. The longitudinal expansion index (LEI) and the volumetric expansion index (VEI) depend on both the density and moisture contents of the extrudate and dough and were calculated using the equations indicated by Alvarez-Martinez et al (1988). The density of the dough in the extruder was computed using the equation indicated by Kokini et al (1992a) and the density of the extrudate was the bulk density of the extruded fish feed.

Viscosity Measurement

The computer-recorded torque and screw speed values were used to calculate shear stress and the stress rate of material in the extruder channel, respectively, when the extruder was assumed to be a coaxial cylinder-shaped viscometer. The extruder could be regarded as two coaxial cylinders (viscometer) containing an inner cylinder (screw) of radius r_i and length L (helical screw length) and an outer cylinder (barrel) of radius r_o (Rogers 1970; Lu et al 1992). The rotation of a screw in an extruder barrel is related to the rotation of a spindle in the cylinder of a viscometer. Screw radius changes along with screw length for a tapered screw (Fig. 1) but spindle radius is constant. Thus, a correction for the radius of the inner cylinder is required

$$\tau_s = \frac{Tor}{2\pi (r_{corr})^2 L_s} = C_{ss} Tor \tag{4}$$

$$\dot{\gamma}_s = \frac{2\omega r_b^2}{(r_b^2 - (r_{corr})^2)} = C_{sr}\omega \tag{5}$$

where τ_s is the shear stress at screw (N/m^{-2}), r_{corr} is the radius correction due to frustum volume ($[(r^2_{eff1} + r_{eff1} r_{eff2} + r^2_{eff2})/3]^{1/2}$, m), r_{eff} is effective radius including screw root radius and ½ of flight height (m), L_s is the screw length in axial direction (m), C_{ss} is a shear stress constant defined as rotor geometry [$(2\pi r_{corr}^2 L_s)^{-1}$, m^{-3}] $\dot{\gamma}_s$ is the shear rate at screw (sec^{-1}), ω is the angular velocity of rotor [$(2\pi/60)N_{Sc}$, sec^{-1}], r_b is the barrel radius (m), and C_{sr} is the shear rate constant that combines geometric factor in a rotational viscometer (dimensionless).

Shear stress expressed as the SI unit N/m^2 indicates how much force is applied to move a unit of area. It is a function of the mechanical torque and the geometry of the rotor in coaxial cylindrical viscometers. Equation 4 can be used to calculate the shear stress at the screw surface (Rogers 1970). Furthermore, the shear rate is the rate at which a material sustains deformation or movement. The shear rate at the screw is a function of the rotation speed and the rotor geometry (Equation 5). Combining Equations 4 and 5 the apparent viscosity can be obtained from

$$\eta = \frac{\tau_s}{\dot{\gamma}_s} = \frac{C_{ss} Tor}{C_{sr}\omega} \tag{6}$$

Equations 4 to 6 neglect the flank clearance and what happens in the flank region because the flank effect was assumed to be negligible.

RESULTS AND DISCUSSION

Viscosity Model

Equation 1 did not closely fit the experimental data (R^2 =0.739), because it did not consider the particle size influence. When different exponential models based on Equation 1 with a multiplying particle size diameter term (d_{ps}) were used to describe the data, the R^2 decreased as the exponent term (linear, quadratic, or cubic) on particle diameter increased. When exponential models with the reciprocal diameter (d_{ps}^{-1}) were used to describe the data, the R^2 increased as the exponent term (linear, quadratic, or cubic) on particle diameter increased. Thus, the viscosity had an inverse relationship with the particle size. The best empirical model is presented as Equation 7 and its parameters are shown in Table II. This model includes the effects of particle size on viscosity and shear rate and of initial moisture content on viscosity. The positive sign of the ($\Delta E/R$) term and the reciprocal temperature show that any viscosity increase was caused by decreasing product temperature over the range of temperatures studied. These results are consistent with the results of other studies (Harper et al 1971; Chen et al 1978; Bhattacharya and Hanna 1986; Kokini et al 1992 a, b).

$$\eta = m\dot{\gamma}^{(n-1)} \exp\left[\frac{\Delta E}{RT}\right] \exp(B_2 MC) \exp\left[\frac{b_3'}{\pi d_{ps}^3/6}\right] \tag{7}$$

where b'_3 is the constant for particle size volume ($B_3\,\pi\,6^{-1}$, mm^3), and B_3 is a constant for particle size (mm).

Figure 2 shows that the response surface of the viscosity changes at different particle sizes, moisture contents, and at a product temperature of 112°C when the screw speed remained at 70 rpm. The effect of product temperature on viscosity was not as significant ($P > 0.05$) as the effects of initial moisture content and particle size. Moreover, viscosities had similarly shaped response surface curves at 40 and 100 rpm screw speeds for the same initial moisture and particle size diameter. When the material had a lower moisture content and larger particles, the viscosities were the highest at all temperature profiles. The viscosity decreased as particle size decreased. Increasing moisture content also resulted in a decrease in viscosity, because water acts as a plasticizer in the extruder channel, and then shear stress decreases.

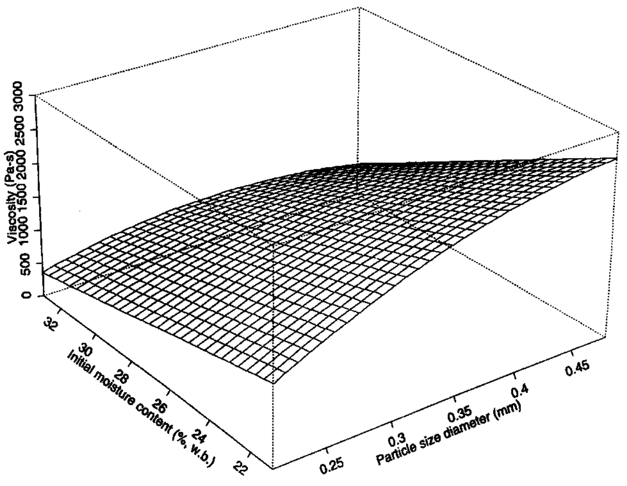

Fig. 2. Viscosity at a constant 70 rpm screw speed and 112°C product temperature.

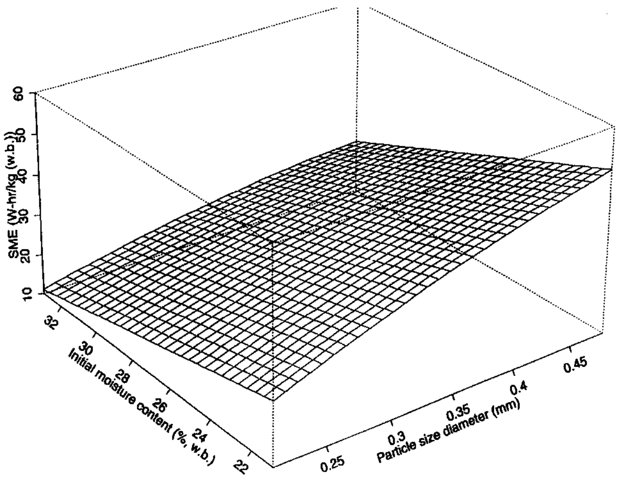

Fig. 3. Specific mechanical energy (SME) at a constant 70 rpm screw speed and 112°C product temperature.

The fish feed contained a high amount of protein (45.2%, db), mainly from the 32.0% soybean meal in the formula. The flow behavior of the fish feed ($n = 0.246$) indicated a high degree of shear thinning. Chen et al (1978) reported that the flow behavior index of soy protein concentrate containing 56.7% protein (db) was 0.127. Similarly, when the ratio of soy protein concentrate and corn gluten meal increased, the flow behavior index decreased (Bhattacharya and Hanna 1986).

Equations 4 to 6 consider the rotation of the screw in an extruder barrel as related to the rotation of a spindle in the cylinder viscometer, this implies the approximation of a Newtonian simple shear in power law fluids. In concentric cylinders of uniform diameter, this approximation carries an error that is a function of the difference between the two concentric cylinders and the flow behavior index (Steffe 1996). The potential error due to this assumption was not included in this analysis because in this study the concentric cylinders had a variable gap due to nonuniform diameters between the cylinders (Fig. 1). Nonetheless, in estimating the shear rate this potential error should be taken into consideration in further studies.

Effects on Mechanical Response

The torque declined as initial moisture content increased because water reduced the viscosity of the extrudate and resulted in decreased shear stress. The R^2 values of the power-law models for torque as a function of initial moisture content of the feed mix for particle sizes of 0.21, 0.37, and 0.48 mm were 0.745, 0.882, and 0.859, respectively. Additionally, the shear stress or torque was dependent on initial moisture content, particle diameter, interaction of moisture and temperature, interaction of particle diameter and moisture, interaction of particle size and particle diameter, interaction of screw speed and moisture, and interaction of screw speed and particle diameter ($P < 0.01$).

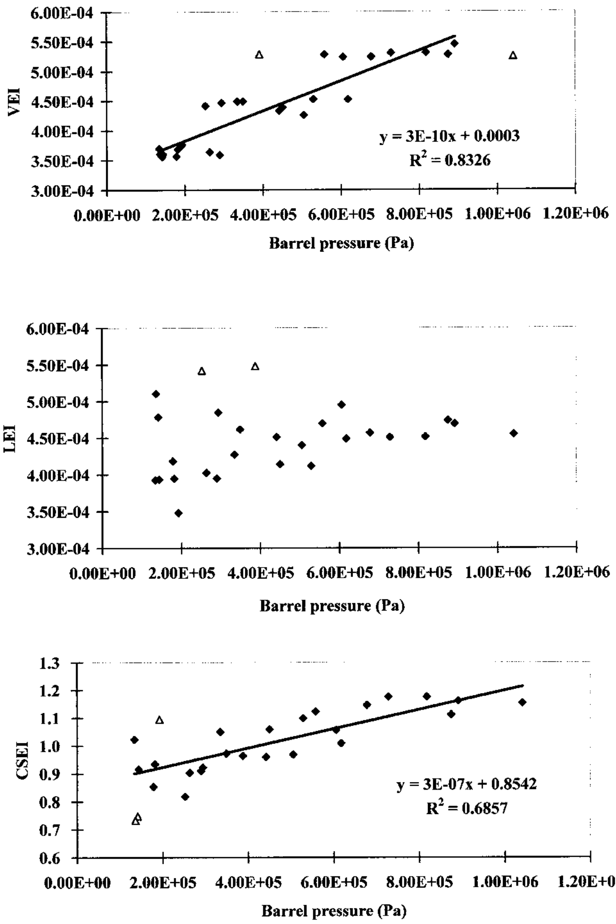

Fig. 4. Barrel pressure effects on longitudinal expansion index (LEI) and volumetric expansion index (VEI), and cross-expansion ratio (CSEI).

The SME was highest when the material had a lower moisture content and larger particles (Fig. 3). The larger friction was generated by shearing the larger particles at a lower water content, and hence, the extruder required more energy to operate with the larger particles. Furthermore, the SME greatly decreased with decreasing particle size at a low moisture content. When particles became too small to be sheared, the extruder needed less energy to deal with them. Increasing moisture content also resulted in a decrease in the SME, because the water reduced the viscosity of the extrudate, which is reflected in decreased shear stress. Figure 3 shows the effect of particle size and initial moisture content on SME at a constant screw speed (70 rpm) for a product temperature of 112°C. The response surface curves at product temperatures of 99 and 124°C were shaped similarly.

Figure 4 shows the relationship between barrel pressure and the expansion indexes. From the correlation analysis, barrel pressure was related linearly to the cross-sectional expansion index ($R^2 = 0.686$). Similarly, the correlation between barrel pressure and the LEI was very low ($R^2 = 0.160$). The VEI increased linearly as the barrel pressure increased ($R^2 = 0.833$). These results could be explained by considering that pressure was important to produce the extrudate with a uniform volume over the range of processing conditions tested. Because the CSEI and the LEI correlate negatively with each other, and the VEI was the product of the CSEI and the LEI, the VEI seldom changed over the range of conditions studied.

CONCLUSIONS

The torque-screw speed measurement was used to develop a viscosity model equation (Equation 7) that considers shear rate, product temperature, moisture content, and particle size. The particle diameter was related directly to viscosity. The viscosity was the highest for the material with a lower moisture content and a larger particle size, because greater friction was generated by shearing the larger particles at a lower water content. The average flow of the fish feed ($n = 0.246$) indicated a high degree of shear thinning. The torque, barrel pressure, and SME decreased as the moisture content was increased because the water acts as a plasticizer that decreases viscosity. The barrel pressure was important in producing extrudate with a uniform volume over the range of processing conditions tested because it had a strong correlation with the volumetric expansion. Because greater friction was generated by shearing the larger particles at a lower water content, the extruder required more energy to deal with the larger particles. When the particles became too small to be sheared, the extruder required less energy to process them. The viscosity model developed in this study can be of application in the development of large scale extrusion models that determine the effect of particle size of the feed material on the extrudates.

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