

Empirical Modeling of Die Pressure, Shaft Torque, SME, and Product Temperature of Rice Flour in a Corotating Twin-Screw Extruder

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ABSTRACT

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Empirical models for predicting die pressure, product temperature, shaft torque, and specific mechanical energy (SME) input based on rice flour extrusion using a DNDL-44/28D Buhler twin-screw extruder are presented. The models incorporate the effects of shear rate, barrel temperature, moisture content, flow rate, and screw geometry. The models were tested using rice flour at various screw configurations and extrusion conditions. Die pressure is a function of moisture content, product temperature, and flow rate. By testing the die pressure model, we found that, within the experimental range tested, die pressure was not

significantly affected by barrel temperatures and screw configurations. Product temperature and shaft torque are functions of shear rate, moisture content, flow rate, barrel temperature, and screw configuration. Introducing the effect of screw configuration into the models for temperature and shaft torque resulted in an overall improved model performance. Predictions of various models gave good results. Validations of various models were verified using different screw geometries and other processing variables with reasonable accuracy. Extrusion tests indicated that the developed predictive models can be of use for extrusion processing.

Extrusion is an important manufacturing method in many food industries. The extrusion process is a continuous operation with variable thermal and mechanical energy input. The process is particularly useful for obtaining a uniformly processed product. With flexible combinations of screw elements, many screw configurations with different characteristics could be used in the twin-screw extrusion processes. The intermeshing corotating extruder is of special importance owing to its high efficiency in mixing, elimination of stagnant zones, and self-wiping action of elements (Bravo et al 2000). Considerable experimental and analytical work has been directed toward understanding the operating characteristics of the extrusion process. It is important that further extrusion studies provide additional and quantitative understanding, in an engineering context, of the interactions between the extruder design, operating conditions of the extruder, and the change of material characteristics (Yacu 1985).

The effect of extrusion process parameters on system parameters has been well examined by researchers (van Lengerich 1984; Meuser and van Lengerich 1984; Yacu 1985; Della Valle et al 1987, 1989; van Lengerich et al 1989; Meuser and Wiedmann 1989; Zuilichem et al 1992; Weert et al 2001). Among system parameters, product temperature (PT) and specific mechanical energy (SME) have decisive effects on the functionality of extruded food products when reaction occurs during extrusion (Meuser and Wiedmann 1989). Measurements of extrusion pressure help to understand the rheological properties of paste (Li and Bridgwater 2000). Expansion, solubility, and texture are features expected from extruded products among the various target functional properties, all of which are defined by moisture content, viscosity, and thermomechanical history, experimentally represented by SME (Della Valle et al 1993), which is calculated from the screw shaft torque. Every extruder is limited by shaft torque and die pressure due to limitations on the main drive power of the extruder and mechanical

limitations on the die plate and extruder itself. The modeling of die pressure, shaft torque, and product temperature is of practical use for predicting extruder performance and helping extrusion production.

Numerous researchers have modeled the extrusion process, including pressure and temperature (Yacu 1985; Zuilichem et al 1992; Sastrohartono et al 1995; Tibbetts and Wen 1998; Bravo et al 2000; Li and Bridgwater 2000; Weert et al 2001; Jaluria 2003; Russell et al 2003). But the modeling of twin-screw extruders for accurate predictions of the system parameters such as pressure, temperature, torque, and SME is not easy, mainly because of the complexity of the screw geometry and the lack of accurate measurement for rheological properties of materials within the extruder. The effects of extrusion processing variables on viscoelasticity of food materials are simply not possible to measure online. Without accurate measurements for rheological properties, theoretical modeling of extrusion system parameters will not be practical. Empirical modeling of extrusion system parameters provides an alternative to predict extruder performance without considering rheological properties of extruded food materials.

The objectives of this study were to present empirical models considering different screw geometries and processing conditions for a twin-screw corotating extrusion. This work is focused on processing of rice flour and is primarily concerned with the evaluation of die pressure, product temperature, shaft torque, and SME input. This serves as the basic information required for the evaluation of the extruder performance. Die pressure was first modeled based on the pressure model given by Shenkel (1966). More variables, such as screw geometry factor, shear rate, barrel temperature, and flow rate, are introduced into the temperature, shaft torque, and SME models.

MATERIALS AND METHODS

The experiments were conducted with a corotating twin-screw extruder (DNDL-44/28D, Buhler, Uzwil, Switzerland). The extruder includes seven barrels (each 4 L/D, screw length/screw diameter) and a die holder plate (0.5 L/D). Total machine L/D is 28.5. Four separate temperature-controlled, oil-circulating units were connected to the extruder barrels to maintain a preset temperature. Cooling water was connected to the first feed barrel. The second and last barrels were allowed to have their own temperatures. Barrels 3 and 4 were connected to one oil-circulating heater. Barrels 5 and 6 were connected to another oil-circulating heater. A temperature probe and a pressure transducer were inserted into the extruder channel right before the die to measure the product temperature

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(PT) and pressure at the entrance of the die. The extruder has digital displays for operating variables such as barrel temperature (°C) and screw speed (rpm) and for system parameters such as torque (% and Nm), PT (°C), and pressure (bar) developed during extrusion. Shaft torque is a percentage of maximum torque. It can be displayed as % and Nm. SME input is calculated as

$$SME = \frac{M_d \omega}{\dot{m}} \quad (1)$$

where SME is whr/kg, M_d is torque (Nm); ω is angular velocity (radian/sec, 1 rpm = $2\pi/60$ radian/sec), \dot{m} is throughput (kg/hr) (van Lengerich et al 1989).

Rice flour (Rivland Partnership, Houston, TX) at 9% moisture content (wet basis) was used as feed material. Rice flour was added to the extruder with a loss-in-weight feeder (K-ML-KT20, K-Tron AG, Industrie Lenzhard, Niederlenz, Switzerland). Water was added directly in the feed barrel from an electromagnetic flow metering system (Proline Promag 50, Endress + Hauser Flowtec AG, Reinach, Switzerland). This system permits precise control of the water flow rate. The steady state of processing conditions was achieved as indicated by constant pressure, temperature, and torque readings. Extrusion conditions as given in Table I are 1) die geometry with two circular die holes 3 mm in diameter and 6 mm long; 2) screw configurations as in Table II; 3) barrel temperatures of 70, 100, and 130°C; 4) feed flow rate of 42–53 kg/hr; 5) moisture content of 16.5–32.5% (wb); 6) screw speed of 350–580 rpm.

Screw elements 1–3 represent forward conveying elements with different pitches (Table II). Screw elements 4 and 5 are kneading elements with forward and reverse directions, respectively. Each kneading element consisted of four adjacent bilobal disks (5 mm thick) with stagger angles of +45° (forward) and -45° (reverse). Screw elements 6 and 7 are both one-third cut of forward and reverse conveying elements with a pitch of 44 mm. Screw configurations were chosen to cover the range of the pressure and torque of the extruder. Screw configurations with more reverse elements (screw configurations 1 and 4) would result in higher shaft torque and higher shearing during extrusion. It corresponds to higher SME. Screw configurations without reverse elements (screw configurations 2 and 3) would result in higher pressures. Different numbers of kneading elements and conveying elements were also considered in the design of screw configurations.

When modeling temperature, shaft torque, and mechanical energy dissipation, the screw geometry is an important factor for

responses of system parameters. Screws with more kneading elements and more reverse elements will result in more mechanical energy input, which will increase product temperature more rapidly than screws with lower shearing elements. Screw geometry factor (Yacu 1985; Zuilichem 1992) is described as

$$C_{ip} = \frac{\pi^4 D_c^3 D \tan \theta_p}{2h} + m \left(\frac{\pi^2 D^2 e C_c}{\alpha} + \frac{8\pi^2 I^3 e}{\epsilon} + \frac{\pi^2 I^2 h \sqrt{D^2 - I^2}}{2\delta} \right) \quad (2)$$

where D_c is the equivalent twin-screw diameter estimated by

$$D_c = \frac{2}{\pi} (\pi D - \sqrt{2Dh}) \quad (3)$$

where D is screw diameter (m) and h is screw channel depth (m).

C_c is the equivalent twin-screw circumference estimated by

$$C_c = 2(\pi D - \sqrt{2Dh}) \quad (4)$$

Screw geometry specifications and screw factors calculated based on Equation 2 are given in Table III.

The shear rate within the channel was estimated as (Yacu 1985; Harper and Tribelhorn 1992; Rauwendaal 2000, 2001, 2003)

$$\dot{\gamma} = \frac{\pi D_c N}{h} \quad (5)$$

where $\dot{\gamma}$ is shear rate (sec) and N is screw speed (rpm).

A factorial experimental design with duplicates was used to evaluate the effects of screw speed, moisture content, barrel temperature, and screw configuration on product temperature, pressure, shaft torque, and SME input. Regression analyses were performed using MATLAB software (v. 6.0, The Mathworks, Natick, MA) for relationships between independent and dependent variables of extrusion processing.

RESULTS AND DISCUSSION

Die Pressure Modeling

For a power law fluid, the pressure drop through a tubular die is given by Shenkel (1966)

$$P = m_0 \left(\frac{3n+1}{n\pi R^3} \right)^n \left(\frac{2L}{R} \right) e^{AT} e^{BMC} q^n \quad (6)$$

A nonlinear regression analysis of the rice flour extrusion with 16.5–28% moisture content (wb), temperature of 115–184°C, flow rate of 43–51 kg/hr, and screw speed of 350–580 rpm with screw

TABLE I
Extrusion Processing Conditions for Different Extrusion Runs

Extrusion Runs	Screw Configuration	Barrel Temp (°C)	Screw Speed (rpm)	Moisture Content (%)	Flow Rate (kg/hr)
1	Screw 1	70	350/450/580	16.5/18.5/20.5/22.5/24.5/28	43/45/47/49/51
2	Screw 1	100	350/450/580	22.5/24.5/28	45/47/50
3	Screw 2	100	350/450/580	22.5/24.5/28	45/47/49
4	Screw 2	130	350/450/580	22.5/24.5/28	45/47/49
5	Screw 3	70	350/450/580	18.5/20.5/22.5/24.5/28	42/44/46/49
6	Screw 4	70	350/450/580	22.5/24.5/28/30/32.5	47/49/51/53

TABLE II
Screw Configurations

Type of Screw Element	Length (mm)	Pitch (mm)	Direction	No. of Screw Elements			
				Screw 1	Screw 2	Screw 3	Screw 4
1	66	66	Forward	4	4	4	5
2	44	44	Forward	9	9	9	9
3	33	33	Forward	10	12	11	9
4	20	Polypack	Forward	6	8	6	2
5	20	Polypack	Reverse	1	1	1	1
6	14.7	44	Forward	5	0	5	5
7	14.7	44	Reverse	2	0	0	5

configuration 1 (Table I of extrusion run 1) gave the die pressure and processing variables relationship

$$P = 1.734 \times 10^{12} e^{\frac{5971.84}{T}} e^{-0.07279MC} q^{-9.682} \quad (7)$$

where P is die pressure (bar), T is product temperature (K), MC is moisture content (%), and q is flow rate (kg/hr).

The regression analysis for the determination of the desired constants used 21 data points and yielded a regression coefficient (R^2) of 0.889 and a slope of 0.976, indicating a good fit of the pressure data. A plot of the modeled data versus the experimental data from these 21 extrusion data points is illustrated in Fig. 1. Similar results were found by Levine (1982) for hard wheat flour extrusion.

Model validations of the die pressure model were verified using different screw geometries, barrel temperatures, and other processing variables (Table I extrusion runs 2–6). A plot of the observed versus predicted die pressure (data from extrusion runs 2–6) corrected for moisture content, product temperature, and flow rate using Equation 7 is shown in Fig. 2. The slope of 1.09 obtained by a linear regression with the corresponding $R^2 = 0.899$ indicates that the predictions are good. Prediction results imply that the pressure model (Equation 7) obtained from extrusion run 1 is independent of the screw geometries and barrel temperatures.

Shaft Torque Modeling

Although the die pressure can be predicted from Equation 7, product temperatures must be obtained to incorporate into the pressure model. Product temperatures can be obtained only after extru-

sion runs. Efforts are needed to model the product temperature, which results from mechanical energy input and thermal energy input. The thermal energy input varies with changes of barrel temperature. The SME input is calculated from Equation 1. It means that shaft torque modeling is necessary before beginning efforts for temperature modeling.

Both screw speed and moisture content affect the changes of shaft torque during extrusion. Increasing moisture content decreases shaft torque while increasing screw speed also decreases the shaft torque. Similar results were found by Onwulata et al (1994) for corn meal extrusion. Higher shaft torque is associated with the higher thermal energy input of higher barrel temperature. Different screw configurations also have different effects on changes of shaft torque. Screw configuration with more reverse elements (Screw 4) resulted in higher shaft torque compared with Screw 1 with fewer reverse elements. It is likely that moisture content, screw speed, barrel temperature, and screw geometry should be considered in shaft torque modeling. A nonlinear regression analysis of extrusion run 1 gave a shaft torque and processing variables relationship of

$$\text{Torque} = 81267.18 \gamma^{0.6105} e^{-0.02511MC} q^{-0.4859} \quad (8)$$

The regression analysis for the determination of the desired constants used data points from extrusion run 1 and yielded values of $R^2 = 0.980$ and slope = 1.04, indicating a good fit of the shaft torque data. A plot of the modeled data versus the experimental data from extrusion run 1 is illustrated in Fig. 3. The shaft torque model (Equation 8) underestimated experimental shaft torque of

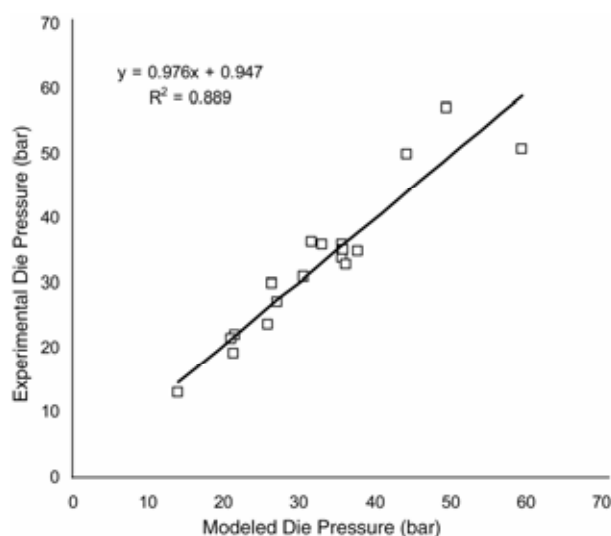


Fig. 1. Modeled die pressure (correction for moisture content, die temperature, and flow rate) using Eq. 7 vs. observed data for extrusion run 1.

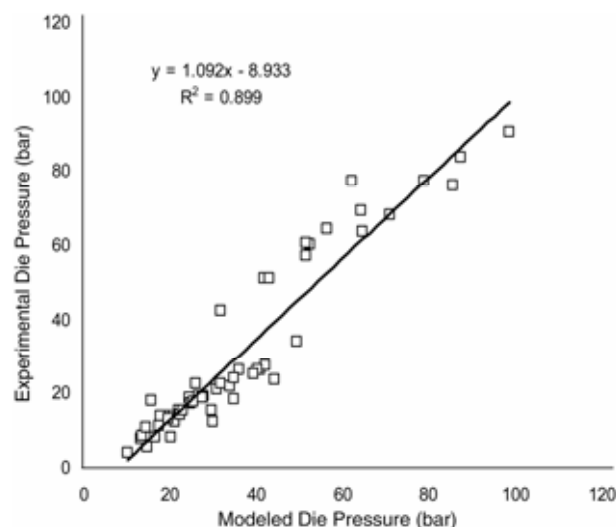


Fig. 2. Predicted die pressure (using Eq. 7 with correction for moisture content, die temperature, and flow rate) vs. observed data for extrusion runs 2–6.

TABLE III
Screw Element Details

Geometry ^a	Type of Screw Elements						
	1	2	3	4	5	6	7
Screw flights	2	2	2	2	2	2	2
h (10^{-3} m)	8.56	8.56	8.56	8.56	8.56	8.56	8.56
e (10^{-3} m)	2.8	1.8	1.3	5	5	1.8	1.8
α (10^{-3} m)	0.25	0.25	0.25	0.25	0.25	0.25	0.25
ϵ (10^{-3} m)	0.07	0.07	0.07	0.07	0.07	0.07	0.07
δ (10^{-3} m)	3	3	3	3	3	3	3
C_c (m^3)	0.420	0.271	0.197	0.312	0.144	0.813	0.0111

^a Specifications (m): h , screw channel depth; e , screw flight width in axial direction; α , distance between the screw flight tip and the inside surface of the barrel; ϵ , clearance between flight tip and bottom of two opposite screws; δ , space between flights of opposite screws parallel to each other; C_c , equivalent twin screw circumference.

Screw 1 with increased barrel temperature of 70–100°C. The shaft torque model (Equation 8) also underestimated experimental shaft torque of the different screw configurations with more reverse elements. The shaft torque model verification indicates that the barrel temperature and screw geometry should be incorporated into the shaft torque modeling.

Our experimental extrusion runs showed that the screw factor in Equation 2 of screw elements underestimated the effects of the reverse element in increasing the shaft torque and die temperature. Without any adjustment of screw factors, it is good for predicting the shaft torque of the screw geometries without reverse screw elements. A correction factor was applied to Equation 2 and screw factors for reverse elements were calculated in Table III.

A nonlinear regression analysis of extrusion runs with the correction for shear rate, moisture content, screw geometry, flow rate, and barrel temperature gave torque and processing variables relationship as

$$\text{Torque} = 60264.68 \dot{\gamma}^{-0.4722} e^{-0.04525MC} \left(\sum_{\text{all screw elements}} \frac{1}{C_{1\rho}} \right)^{0.5717} e^{-\frac{2323.25}{T_b}} q^{0.4814} \quad (9)$$

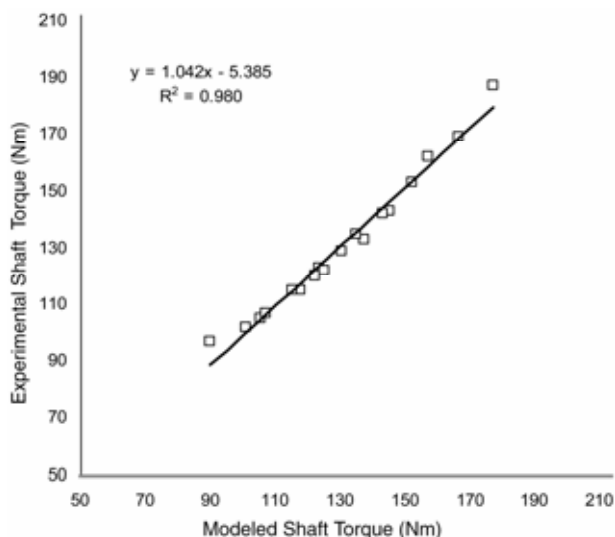


Fig. 3. Modeled shaft torque using Eq. 8 vs. experimental shaft torque for extrusion run 1.

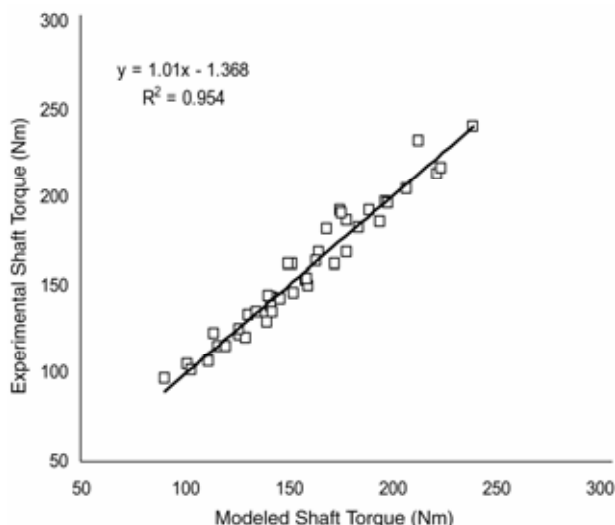


Fig. 4. Modeled shaft torque (correction for shear rate, moisture content, flow rate, screw geometry, and barrel temperature) using Eq. 9 vs. experimental shaft torque.

The regression analysis for the determination of the desired constants used data points from extrusion runs 1–4 and yielded values of $R^2 = 0.954$ and slope = 1.01, indicating a good fit of the shaft torque data. A plot of the modeled shaft torque data versus experimental shaft torque data from extrusion runs 1–4 is illustrated in Fig. 4. As can be seen, the prediction of shaft torque is quite good for all data points.

Model validations of the shaft torque model were verified using different screw geometries and other processing variables (Table I extrusion runs 5 and 6). A plot of the observed shaft torque versus predicted shaft torque (data from extrusion runs 5 and 6) corrected for shear rate, moisture content, screw geometry, flow rate, and barrel temperature using Equation 9 is shown in Fig. 5. Slope = 1.05 obtained by linear regression with corresponding $R^2 = 0.984$ indicates that the predictions of shaft torque are very good. The shaft torque model verification indicates that screw geometries were successfully incorporated into the shaft torque modeling.

SME Input Modeling

Using modeled shaft torque data points of extrusion runs 1–4 using Equation 9 and incorporating these modeled shaft torque

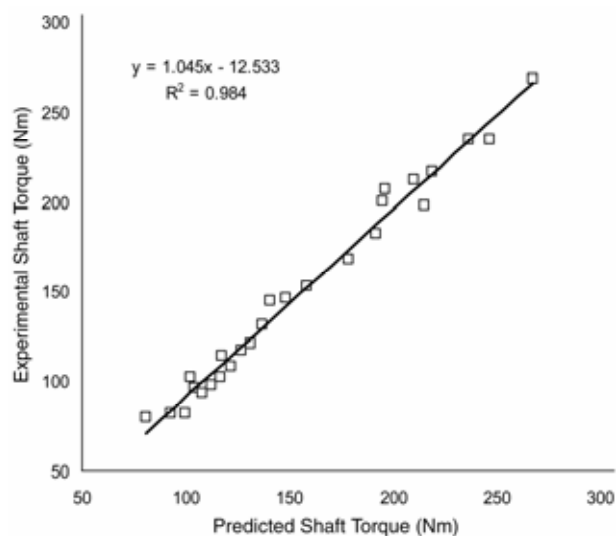


Fig. 5. Predicted shaft torque using Eq. 9 for data from extrusion runs 5 and 6 vs. experimental shaft torque.

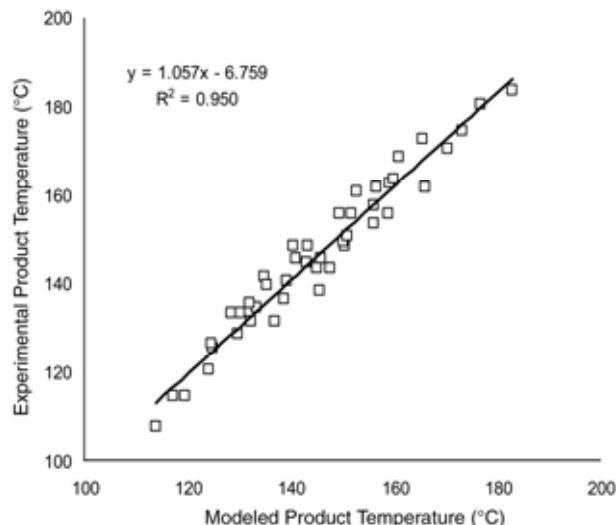


Fig. 6. Modeled product temperature (correction for shear rate, moisture content, flow rate, screw geometry, and barrel temperature) using Eq. 10 vs. experimental die temperature.

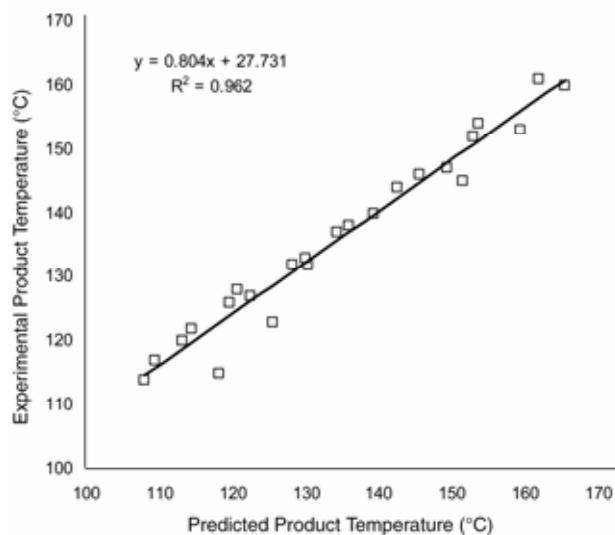


Fig. 7. Predicted product temperature using Eq. 10 for data from extrusion runs 5 and 6 vs. experimental die temperature.

data into Equation 1 to predict SME input yielded values of $R^2 = 0.955$ and slope = 1.05 for predicted and experimental SME data, indicating a good fit of SME data. Model validations of the SME model were verified using different screw geometries and other processing variables (Table I extrusion runs 5 and 6). Slope = 1.05 obtained by a linear regression with the corresponding $R^2 = 0.978$ for predicted and experimental SME data indicates that the predictions of SME are very good. SME model verification also indicates that screw geometries were successfully incorporated into the shaft torque modeling.

Product Temperature Modeling

Shaft torque modeling method was useful for product temperature modeling with similar fits. A nonlinear regression analysis of extrusion runs with the correction for the shear rate, moisture content, screw geometry, flow rate, and barrel temperature gave a product temperature and processing variables relationship of

$$\text{Exp}(1/T) = 1.006734\dot{\gamma}^{-0.0001441} e^{-0.00004438MC} \left(\sum_{\text{all screw elements}} \frac{1}{C_{1j}^{1j}} \right)^{-0.00008119} e^{-\frac{0.4646}{T_b}} q^{-0.001383} \quad (10)$$

A plot of the modeled product temperature data using Equation 10 versus the experimental product temperature data from extrusion runs 1–4 is illustrated in Fig. 6 ($R^2 = 0.95$ and slope = 1.06). As can be seen, the prediction of the product temperature is quite good for all data points.

Model validations of the product temperature model were verified using different screw geometries and other processing variables (Table I extrusion runs 5 and 6). A plot of the observed product temperature versus the predicted product temperature (data from extrusion runs 5 and 6) using Equation 10 is shown in Fig. 7. Although the slope = 0.804 obtained by linear regression is less than one, the y axial intersection compensated for the slope and gave very good matches of predicted product temperature and experimental product temperature. The corresponding $R^2 = 0.962$ also indicates that the predictions are very good. Product temperature model verification indicates that screw geometries were also successfully incorporated into the product temperature modeling.

With the success of modeling the product temperature, the die pressure can be modeled from processing parameters instead of using experimental product temperatures. Product temperatures were predicted using model Equation 11, then these calculated product temperatures were used in the die pressure model Equation 7 to

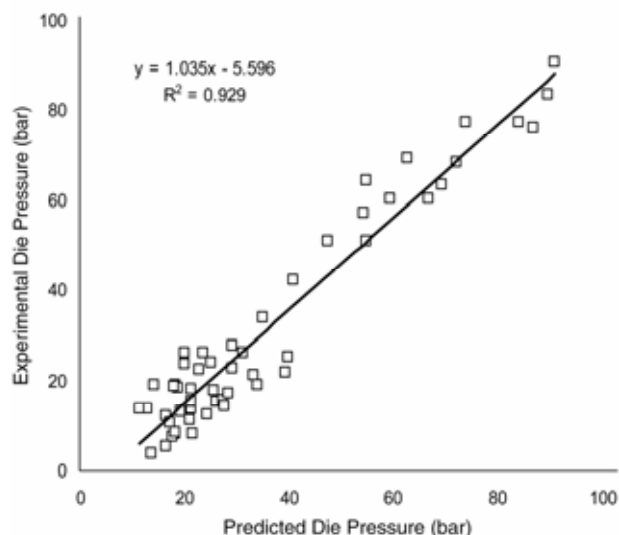


Fig. 8. Predicted die pressure using Eq. 7 with the product temperature predicted by Eq. 10 for data from extrusion runs 2 and 6 vs. experimental die pressure.

predict die pressures. A plot of the predicted die pressure data using Equations 7 and 11 versus the experimental die pressure data from extrusion runs 2–6 is illustrated in Fig. 8 ($R^2 = 0.929$ and slope = 1.03). As can be seen, the prediction of the die pressure is quite good for all data points

CONCLUSIONS

Empirical models for predicting the die pressure, product temperature, shaft torque, and SME input based on rice flour were presented and tested using various screw configurations and extrusion conditions. The models include the effects of shear rate, barrel temperature, moisture content, flow rate, and screw geometry. The model responded well to changes in processing variables, including screw configurations. Die pressure is a function of moisture content, product temperature, and flow rate. Testing the die pressure model, within the experimental range tested, showed that die pressures were not significantly affected by barrel temperatures and screw configurations. Product temperature and shaft torque are functions of the shear rate, moisture content, flow rate, barrel temperature, and screw configuration. Introducing the effects of the screw configuration into the temperature and shaft torque models resulted in an improved model performance. Predictions of various models gave good results. The validation of various models was accomplished using different screw geometries and other processing variables with reasonable accuracy. Screw configurations were successfully included in shaft torque and SME models. Extrusion tests indicated that the developed predictive models can be of use for extrusion processing. This empirical modeling method provided a simple and practical way to model the extrusion process without unnecessary general model assumptions and the need for accurate estimations of rheological properties of food materials, which is usually required for theoretical extrusion process modeling and is usually the reason for unsatisfactory model predictions due to poor estimation accuracies.

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