# SME-Arrhenius Model for WSI of Rice Flour in a Twin-Screw Extruder

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## ABSTRACT

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We have modeled a rice extrusion process focusing specifically on the starch gelatinization and water solubility index (WSI) as a function of extrusion system and process parameters. Using a twin-screw extruder, we examined in detail the effect of screw speed (350–580 rpm), barrel temperature, different screw configurations, and moisture content of rice flour on both extrusion system parameters (product temperature, specific mechanical energy [SME], and residence time distribution [RTD]) and extrudate characteristics (expansion, density, WSI, and water absorption index [WAI]). Changes in WSI were monitored to reveal a relationship between the reaction kinetics during extrusion and WSI. Reaction kinetics models were developed to predict WSI during extrusion. WSI followed a pseudo first-order reaction kinetics model. It became apparent that the rate constant is a function of both temperature and SME. We have developed an adaptation of the kinetic model based on the Arrhenius equation that shows better correlations with SME and distinguishes data from different screw configurations. This adaptation of the model improved predictability of WSI, thereby linking the extrusion conditions with the extruded product properties.

In many food industries extrusion is an important manufacturing method. Uniformly processed products can be obtained in a continuous operation with variable thermal and mechanical energy input. Screw configurations in twin-screw extruders can vary widely and enable broad processing capabilities with respect to time-temperature history and residence time distribution (RTD) of the mass inside the extruder. Considerable experimental and analytical work has been directed toward understanding the operating characteristics of the extrusion process and the effect on food substrates (Colonna et al 1989). 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).

Identifying the important variables and parameters for controlling extrusion cooking will allow for a more quantitative understanding of how extrusion processing variables affect thermomechanical transformation of starch materials into the final product. Among the extrusion product properties, expansion, solubility, and texture are regarded as target functional properties. These target functional properties are defined by moisture content, viscosity, and thermomechanical history. According to Della Valle et al (1993), these properties are experimentally reflected by specific mechanical energy (SME). Under the high-shear high-temperature conditions that exist during extrusion processing, starch degradation leads not only to changes in its molecular weight and the molecular-weight distribution but also in the structure of the molecules. This is reflected in changes in melt rheology (Vergnes and Villemaire 1987) and the functional properties of the products such as water solubility (Fitton 1986), water absorption, and dispersion viscosity (Doublier et al 1986).

The extent of both physical and chemical interactions of the material within the extruder is influenced by the residence time distribution (RTD). The RTD gives information about the degree of mixing, the degree of uniformity of shearing on the particles, and the temperature-time combination (Van Zuilichem 1992). Therefore, RTD is a useful tool for the determination of optimal extrusion conditions. The factors reflected in RTD are particularly important for preparing a product of good quality in food extrusion where many biopolymer reactions are involved. In this study, we focused on the mean residence time (MRT). This will be used for the adapted reaction kinetic modeling of water solubility index (WSI) during extrusion.

We set out to uncover the influence of raw material moisture content and extrusion process variables (screw speed and geometry) on the system parameters (product temperature [PT], SME, RTD) and final extrudate properties (expansion, density, and WSI). A systematic evaluation and reaction kinetics modeling of WSI enabled us to link functionality with system parameters such as PT, SME, and RTD.

## MATERIALS AND METHODS

The experiments were conducted with a corotating twin-screw extruder (DNDL-44/28D, Buhler, Uzwil, Switzerland). The extruder has seven barrels each with 4 L/D (screw length/screw diameter) and a die holder plate with 0.5 L/D. The 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 their own temperatures. Barrels 3 and 4 were connected to one circulating oil heater. Barrels 5 and 6 were connected to another circulating oil heater. A temperature probe and a pressure transducer were inserted into the extruder channel right before the die to measure the product temperature (PT) and pressure at the entrance of the die. The extruder has digital displays for torque (% and Nm), PT (°C), and pressure (bar) developed during extrusion. Shaft torque is a percentage of maximum torque. It can be displayed as % or Nm. Specific mechanical energy input (SME) is calculated as

$$\mathrm{SME} = \frac{M_{\mathrm{d}}\,\omega}{\dot{m}} \tag{1}$$

where SME is in whr/kg; $M_{\mathrm{d}}$ is torque in Nm; ω is angular velocity in radian/sec (1 rpm = 2 π/60 radian/sec); and $\dot{m}$ is throughput (kg/hr) (van Lengerich et al 1989).

Rice flour (Rivland Partnership, Houston, TX) at 9% moisture content (wb) was used as feed material. Particle size was determined as 95–100% through U.S. 50 mesh; 45–65% through U.S. 100 mesh; and 25–40% through U.S. 140 mesh. 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 into the feed barrel from an electromagnetic flow metering system (Proline Promag 50, Endress + Hauser Flowtec

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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 (Table I) were 1) die geometry of two circular die holes 3 mm in diameter and 6 mm long; 2) screw configurations as in Table II; 3) barrel temperatures 70 and 100°C; 4) flow rate 35–52.5 kg/hr; 5) moisture content 16.5–28% (wb).

A full-factorial experimental design with duplicates was used to evaluate the effects of screw speed, moisture content, and screw configuration on temperature, pressure, shaft torque, specific mechanical energy (SME) input, and selected properties of extruded rice flour. The response variables of property changes were density, expansion ratio, water solubility index (WSI), and water absorption index (WAI). Additional software (SAS Institute, Cary, NC) was used to analyze the data for relationships between independent and dependent variables of extrusion processing with respect to the prescribed properties of the extrudates using ANOVA with significance established at $P < 0.05$. Software (SPSS, Inc., Chicago, IL) was used to generate three-dimensional graphs to describe complex changes and trends among the different variables.

### Cross-Sectional Expansion Ratio

Expansion ratios of the extruded rice were calculated by dividing the average cross-sectional area of the extrudates by the cross-sectional area of the die orifice. Each value was an average of 10 readings.

### Density

The density of the extrudates was calculated from the mean diameter, weight, and length by assuming they were perfectly cylindrical. Samples were set in the laboratory atmosphere to equilibrate to ambient moisture content over a one-week period before measurement. The product density was obtained by dividing the mass of the sample by the volume. Each value was an average of 10 measurements.

### WSI and WAI Measurement

The measurement methods of WSI and WAI are similar to those provided by Anderson et al (1969). WSI method improvements were made in sample size and calculation method to facilitate experimental control and data reproducibility. The extrudates were first milled to a mean particle size of ≈250–500 μm. One needs to determine the moisture content for every sample. Sample (≈1 g) was accurately weighed and corrected for moisture and dispersed in 25 g of distilled water using a magnetic stirrer at room temperature. After stirring for 1 hr, the dispersions are transferred into centrifuge tubes and centrifuged at 3,000 × $g$ for 10 min. The supernatant was decanted into a tared evaporating dish for determination of solids content (WS = g of dry solids/1 mL of distilled water). The sediment was weighed to determine the WA (g of water /1 g of dry solids).

$S_1$ (amount of solids in supernatant), $S_2$ (amount of solids in sediment), $W_1$ (amount of water in supernatant), and $W_2$ (amount of water in sediment) could be calulated by four equations

$$W_1 + W_2 = 25 + W \times \mathrm{MC\%} \tag{2}$$

$$S_1 + S_2 = W \times (1 - \mathrm{MC\%}) \tag{3}$$

$$S_1 = W_1 \times \mathrm{WS} \tag{4}$$

$$W_2 = S_2 \times \mathrm{WA} \tag{5}$$

where MC% is the moisture content of samples and $W$ is the sample weight of wet solids.

$S_1$ can be calculated from the equation

$$S_1 = \frac{25 + W \times \mathrm{MC\%} - W \times (1 - \mathrm{MC\%}) \times \mathrm{WA}}{1/\mathrm{WS} - \mathrm{WA}} \tag{6}$$

The indices are defined by

$$\mathrm{WAI} = \frac{\text{wt of sediment}}{\text{dry solids}} = \frac{S_2 + W_2}{W \times (1 - \mathrm{MC\%})} \tag{7}$$

$$\mathrm{WSI}\ (\%) = \frac{\substack{\text{wt of dissolved solids} \\ \text{in supernatant}}}{\text{dry solids}} = \frac{S_1}{W \times (1 - \mathrm{MC\%})} \times 100 \tag{8}$$

The method from Anderson et al (1969) requires completely transferring tested samples from one container to another. One needs to add more water to rinse containers and that an accurate quantity of water and thorough transfer of samples with the little amount of water are important, which are difficult to accomplish. One could avoid these problems by using the methods above.

**TABLE I**
**Extrusion Processing Conditions for Different Extrusion Runs**

| Extrusion Runs | Screw Configurations | Barrel Temp (°C) | Screw Speed (rpm) | Moisture Content (%) |
|---|---|---|---|---|
| 1 | Screw 1 | 70 | 350/450/580 | 16.5/18.5/20.5/22.5/24.5/28 |
| 2 | Screw 2 | 70 | 350/450/580 | 22.5/24.5/28 |
| 3 | Screw 1 | 100 | 350/450/580 | 22.5/24.5/28 |
| 4 | Screw 2 | 100 | 350/450/580 | 22.5/24.5/28 |
| 5 | Screw 3 | 70 | 350/450/580 | 22.5/24.5/28 |
| 6 | Screw 3 | 100 | 350/450/580 | 22.5/24.5/28 |
| 7 | Screw 4 | 70 | 350/450/580 | 22.5/24.5/28 |
| 8 | Screw 4 | 100 | 350/450/580 | 22.5/24.5/28 |

**TABLE II**
**Screw Configurations**

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

### RTD Measurement

This approach utilized a blue dye tracer to visualize the movement of flour and product through the extruder. Blue tracer was prepared by soaking rice flour in a 5% (w/w) food-grade blue #1 solution for 72 hr. The soaked rice flour was then filtered and washed with distilled water until a clear or transparent filtrate (clear but still blue) appeared. At that point, the dye color penetrated the starch granule and the blue dye on the surface of the starch granules should be washed out. The blue tracer was then dried in a laboratory atmosphere to ambient moisture content and mashed to a fine powder. This tracer (soaked tracer) was used for RTD to solve some problems such as blue dye sticking on screws and a longer tailing time during extrusion, which resulted from a direct mixing of rice flour and blue dye.

Blue tracer was injected into the extruder by adding ≈1.5 g of soaked blue tracer at time (*t*) = 0 to the feed channel just above the first screw channel of the extruder. A constant extrusion condition was reached before tracer addition. Samples were collected every 10 sec starting from $t = 0$ with samples collected every 2 sec around the color peak time during extrusion. There are ≈25 data points for every RTD curve of a single extrusion condition. The samples were set at the room temperature over one week, then ground and sieved through a 0.5-mm sieve.

### Blue Color Extraction Method

Ground extrudate sample (1 g) was soaked in 25 mL of distilled water, taking special care to break up any lumps with a glass rod. The samples were sealed with aluminum foil and set at room temperature for 6 hr. A soaking time of 6 hr was experimentally determined to be the optimum. This is a static extraction procedure that is suitable for soaked tracer. After a period of extraction, a glass rod was used to disperse and homogenize the samples. The samples were then centrifuged and absorbance was determined. Blue color concentration was calculated based on a calibration curve of blue color concentration against absorbance. The soaking extraction method handled samples with identical extraction conditions. The test results showed that the data was reliable and reproducible.

### RTD Functions

The *C*-curve describes the distribution of the output tracer concentration as a function of time. To compare these *C*-curves and to make them independent of the process conditions such as the input tracer concentration, the tracer output concentration must be normalized. The normalized distribution of the tracer residence time delivers a differential, *E(t)*-curve, or cumulative, *F(t)*-curve, and RTD curve (Levenspiel 1972). The normalized, differential output tracer concentration curve, *E(t)*-curve, for steady-state conditions (Heppel 1985) is given by the equation

$$E(t) = \frac{C}{\int_0^\infty C dt} \cong \frac{C}{\sum_0^\infty C_i \Delta t_i} \tag{9}$$

where $C$ is tracer concentration appearing at the exit at $t = 0$.

The MRT (Levenspiel 1972) was calculated as

$$t_m = \int_0^\infty tE(t)dt \cong \frac{\sum t_i C_i \Delta t_i}{\sum C_i \Delta t_i} \tag{10}$$

## RESULTS AND DISCUSSION

### Changes of System Parameters During Extrusion

The effect of process parameters on the system parameters was well examined by researchers (van Lengerich 1984; Meuser and Wiedmann 1989). Among system parameters, PT, SME, and MRT have a decisive effect on the functionality of extruded food products when reaction occurs during extrusion (Meuser and Wiedmann 1989). Therefore, only these three system parameters are described in this report.

Screw speed, moisture content, barrel temperature, and screw geometry had significant effects on system parameters. The decreasing moisture content and increasing screw speed increased PT and SME. Increasing barrel temperature increased PT and decreased SME. Screw configurations with more reverse elements, which increased shearing, also increased PT and SME. Similar interrelationships between process and system parameters could be found in literature (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).

Typical RTD curves were represented in Fig. 1 with screw configuration 1 and in Fig. 2 with different screw configurations. With the same moisture content (28%), increasing screw speed shifted RTD and color peaks to the left with decreases in MRT (Fig. 1). Adding reverse screw elements in screw configurations shifted RTD and color peaks to the right with increases in MRT (Fig. 2). MRT can be defined as the ratio of filled volume to the volumetric

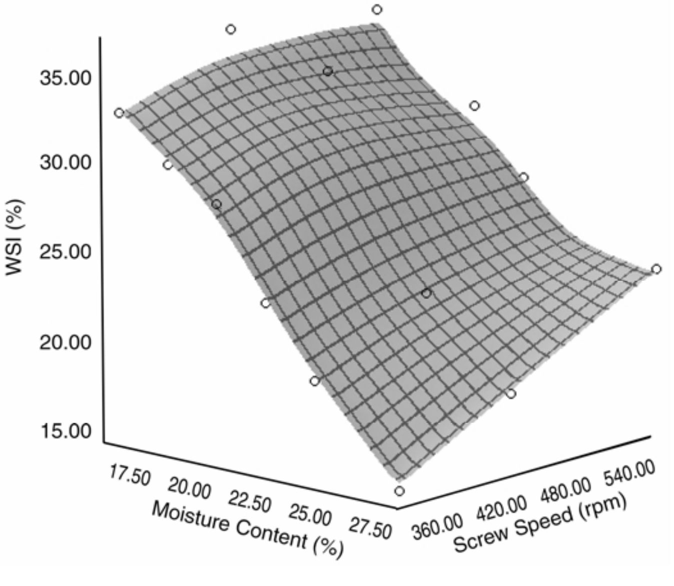

**Fig. 1.** Effect of moisture content and screw speed on water solubility index (WSI) of extruded rice flour for screw configuration 1 with barrel temperature of 70°C.

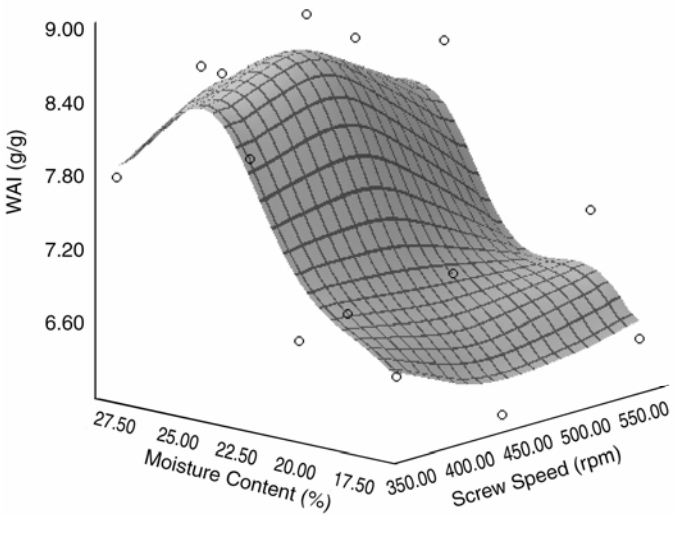

**Fig. 2.** Effect of moisture content and screw speed on water absorption index (WAI) of extruded rice flour for screw configuration 1 with barrel temperature of 70°C.

flow rate of the extruder (Gao et al 2000). In the sections of reverse elements or, in some cases dependent on the pressure generated in screws right before reverse elements, the screws will be fully filled (Jager et al 1992; Tayeb et al 1992; Gao et al 2000), which means an increased MRT compared with partially filled forward screw elements. Adding reverse screw elements also changes the distribution pattern, which results in a broadened distribution and big leakage flow (Tayeb et al 1992). Extrusion with more reverse elements (screw configurations 2 and 4) gave higher MRT of 42–62 sec, while extrusion with fewer reverse elements (screw configurations 1 and 3) gave lower MRT of 22–56 sec. Depending on the extrusion conditions, color peaks observed at the time were 14–45 sec. Color peak time was always delayed by the screw configurations with more reverse elements compared with screw configurations with fewer reverse elements.

MRT of 26–34 sec was observed for the screw configuration 1 and 22–33 sec for screw configuration 3 with lower barrel temperature of 70°C. Increasing barrel temperature from 70 to 100°C increased MRT ≈20 sec for screw configurations 1 and 3 but only 1–3 sec for screw configurations with more reverse elements (screw configurations 2 and 4). Chen et al (1995) also observed an increased MRT with the increase of the barrel temperature. Ruyck (1997) found an increased MRT with a decreased dough viscosity. Jager et al (1992) observed an increased degree of fill with the increase of the barrel temperature. A possible explanation is that the leakage flow is increased with the decrease of viscosity, which results in an increased MRT.

## Changes in Extrudate Properties

Functionalities of extrudate such as solubility and expansion resulted from changes of starch properties due to energy input, which can be presented as a function of PT and SME (Meuser and Wiedmann 1989). Our results also show that PT and SME had significant effects on the changes of extrudate properties.

Expansion ratio increased quickly with the decrease of moisture content for lower screw speeds. With higher moisture content (24.5–28%), the expansion ratio increased with the increase of screw speed but the expansion ratio decreased at higher screw speed (580 rpm). At lower moisture content (16.5–20%), the effects of screw speed on the expansion ratio were not significant ($P > 0.495$). Decrease of expansion ratio was observed with the decrease of screw speed at the lower moisture content. Lower density was observed from higher screw speed no matter what the moisture content was. Lower density was also observed from lower moisture content, no matter what the screw speed was. The highest density occurred when rice flour was extruded with the highest moisture content and the lowest screw speed. Experimental data shows that the expansion ratio increased and density decreased with the increase of the product temperature for all die pressure changes. Expansion ratio increased and density decreased with the increase of SME input. Expansion ratio had small changes when SME input was >150 whr/kg. There were small changes in density for die temperature >160°C. SME input had little effect on the changes of density and expansion ratio when product temperature was fixed.

The effects of processing variables and moisture content on the WSI of the final products are shown in Fig. 2. At lower moisture contents of 18.5 and 20.5%, the influence of moisture content is not significantly different ($P > 0.503$) on the WSI for all screw speeds with the exception of 450 rpm, which gave higher WSI (Fig. 3). WSI increased with the decrease in moisture content. In twin-screw extrusion, the mechanical energies are heavily influenced by the moisture content (Colonna et al 1989). This mechanical energy input was also considered as a major effect on the degree of starch conversion (starch gelatinization and fragmentation) during extrusion (Gomez and Aguilera 1983, 1984; Diosady et al 1985; Colonna et al 1989; Wang et al 1992). At the lowest moisture content of 16.5% with a barrel temperature of 70°C, the highest WSI was observed, which corresponded to the severe extrusion conditions of higher mechanical energy input and resulted in higher product temperature. Increasing barrel temperature, which resulted in increased product temperature, always increased WSI. Increasing screw speed (from 350 to 450 rpm) increased WSI.

Decreased WSI was observed when screw speed increased from 450 to 580 rpm, which corresponded to the decreased residence time. This effect of residence time on product transformation has been reported by Meuser et al (1987) and Vergnes et al (1987) by measuring WSI. The longer the treatment, the more the product is transformed (Colonna et al 1989).

Experimental data shows that WSI increased with the increase of the product temperature for all die pressures at 20–80 bar. The highest WSI occurred at the highest product temperature and the highest SME input. Lower product temperature resulted in lower WSI no matter how much SME input. But at higher SME input (>100 whr/kg), increasing the product temperature caused a quick increase of the WSI. After the product temperature reached 160°C, the changes of WSI were small. Increasing moisture content increased WAI (Fig. 4). Changes in screw speed correspond to small changes in WAI for all samples with the same moisture content.

## Pseudo First-Order Kinetics of WSI

It is widely accepted that starch gelatinization follows pseudo first-order Arrhenius kinetics (Bakshi and Singh 1980; Pravisani et al 1985; Burros et al 1987; Lai and Kokini 1991; Okechukwu et al 1991; Zanoni et al 1991, 1995; Okechukwu and Rao 1996a,b). Researchers also reported a first-order reaction of starch gelatinization during extrusion (Burros et al 1987; Lai and Kokini 1991; Cai and Diosady 1993; Qu and Wang 1994). Extrusion studies (Bhattacharya and Hanna 1987; Cai and Diosady 1993) used MRT as the time variable. Dolan (2003) also concluded that the thermal history and RTD are critical to obtain accurate estimates of kinetic parameters.

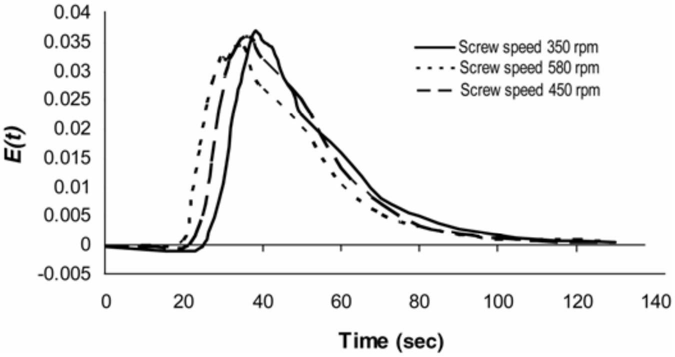

**Fig. 3.** *E(t)* vs. residence time at a moisture content of 28% for screw configuration 1 with barrel temperature of 100°C and different screw speeds.

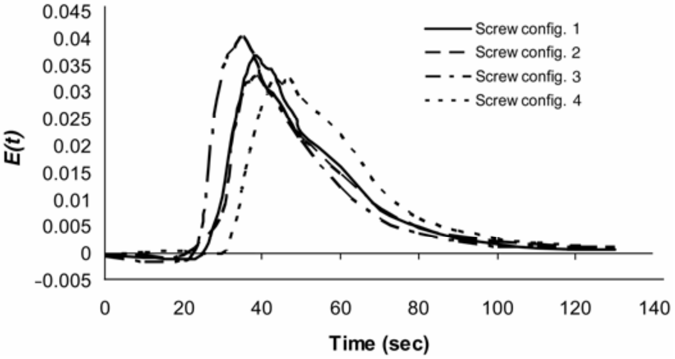

**Fig. 4.** *E(t)* vs. residence time at a moisture content of 28% with barrel temperature of 100°C and different screw configurations.

The rate equation for an *n*th-order reaction is

$$-\frac{d(A)}{dt} = k(A)^n \tag{11}$$

where $A$ = concentration of component $A$ (WSI), $t$ = time (MRT), $k$ = reaction rate constant, and $n$ = reaction order. The order of reaction was determined by regression analysis for each experimental run. The regression analyses gave orders of reaction of ≈1 (Table III). The rate constant range was 0.015–0.05 sec. The correlation coefficients are good except for screw configuration 2. Regression results seemed to suggest that the starch conversion in this twin-screw extruder followed pseudo first-order kinetics, which are the same as those published. Time-concentration dependence could be established for the reaction rate (WSI/MRT in this study, or DG/MRT in literature). Then the reaction kinetics of WSI can be described by the first-order kinetics equation

$$(A) = (A)_0 \exp(-kt) \tag{12}$$

## Arrhenius Model for WSI

The temperature dependence of a rate constant $k$ is often described by the Arrhenius equation

$$k = k_0 \exp\left(-\frac{E_a}{RT}\right) \tag{13}$$

where $k$ = rate constant at temperature $T$, $k_0$ = preexponential factor (sec), $E_a$ = activation energy (Jmol), $R$ = gas constant (8.3 Jmol/K), and $T$ = absolute temperature (K). The experimental results of extrudate WSI were used to estimate the parameters of the Arrhenius model. The results are shown in Table IV. The activation energy range was 10–80 kJmol, depending on the extrusion conditions. The correlation coefficients are good except for extrusion runs 2 and 6. Typical experimental data of extrusion runs 1 and 2 are shown in Fig. 5 with $R^2$ = 0.87 and 0.61, respectively. As can be seen, the Arrhenius model bundled experimental data points. The Arrhenius model was not improved when combining data from extrusion runs 1 and 2 ($R^2$ = 0.84). The Arrhenius parameters for the combined data of extrusion runs 1 and 2 are $k_0$ = 269.94 sec and $E_a$ = 20.17 kJmol.

Using product temperature to characterize reaction kinetics with respect to MRT did not seem appropriate because the sectional residence time for the sudden increase of product temperature is not easily determined. However, SME reflects the thermomechanical history of flour during the entire extrusion. SME has had a significant effect on WSI in our research. SME was also reported to be responsible for fragmentation of starch molecules (Gomez and Aguilera 1983, 1984; Diosady et al 1985) and to catalyze the gelatinization reaction by rupturing intermolecular hydrogen bonds (Wang et al 1992). To overcome the constraint by using only product temperature, we also considered the thermomechanical history (SME) of rice flour during extrusion into reaction kinetics.

## Adaptation of Arrhenius Equation and SME Models

To avoid the autocorrelations between factors we used to construct SME model, the relationships between MRT and SME were analyzed with a GLM procedure using SAS software. The correlations between MRT and SME were not established because high $P$ values and low correlation coefficients were obtained ($P > 0.5$ and $R^2 < 0.08$) for all extrusion runs except runs 1 and 5 ($P$ = 0.0002, $R^2$ = 0.59 for extrusion run 1 and $P$ = 0.0049, $R^2$ = 0.70 for extrusion run 5). As can be seen, the $R^2$ values are very low for extrusion runs 1 and 5. It is clear that MRT is not a function of SME.

By incorporating SME into the Arrhenius equation, the reaction model was greatly improved. For the data from extrusion run 1, the new model gave a very good fitting ($R^2$ = 0.93) (Figs. 6–10). For extrusion run 2, $R^2$ improved from 0.61 to 0.83 (Figs. 9–10). These new reaction models automatically separate the data points of extrusion run 1 from extrusion run 2 (Figs. 9–10).

One could use SME to construct a reaction model or use both SME and absolute product temperature to develop a new model. These two kinds of models gave the same correlation coefficient.

Adaptations of Arrhenius equation were constructed as

$$k = k_0 \times \exp\left(-\frac{E_{\mathrm{SME}}}{\mathrm{SME}}\right) \tag{14}$$

where $k_0$ = preexponential factor (sec) and $E_{\mathrm{SME}}$ = SME constant (whr/kg) (Figs. 6 and 9).

**TABLE III**
**Results of Regression Analysis with Equation 11**

| Extrusion Runs | Screw Configuration | Screw Speed (rpm) | Moisture Content (%) | Barrel Temp (°C) | Order of Reaction | *k* (sec) | *r* |
|---|---|---|---|---|---|---|---|
| 1 | Screw 1 | 350/450/580 | 16.5/18.5/20.5/22.5/24.5/28 | 70 | 1.21 | 0.015 | 0.97 |
| 2 | Screw 2 | 350/450/580 | 22.5/24.5/28 | 70 | 0.78 | 0.041 | 0.76 |
| 3 | Screw 1 | 350/450/580 | 22.5/24.5/28 | 100 | 1.04 | 0.018 | 0.98 |
| 4 | Screw 2 | 350/450/580 | 22.5/24.5/28 | 100 | 0.76 | 0.047 | 0.60 |
| 5 | Screw 3 | 350/450/580 | 22.5/24.5/28 | 70 | 1.19 | 0.020 | 0.96 |
| 6 | Screw 3 | 350/450/580 | 22.5/24.5/28 | 100 | 1.08 | 0.016 | 0.94 |
| 7 | Screw 4 | 350/450/580 | 22.5/24.5/28 | 70 | 0.95 | 0.021 | 0.92 |
| 8 | Screw 4 | 350/450/580 | 22.5/24.5/28 | 100 | 0.87 | 0.027 | 0.88 |

**TABLE IV**
**Results of Regression Analysis with Arrhenius Model**

| Extrusion Conditions | | | | | Model Parameters | | |
|---|---|---|---|---|---|---|---|
| Extrusion Runs | Screw Configuration | Screw Speed (rpm) | Moisture Content (%) | Barrel Temp (°C) | $k_0$ (sec) | $E_a$ (kJ/mol) | *r* |
| 1 | Screw 1 | 350/450/580 | 16.5/18.5/20.5/22.5/24.5/28 | 70 | 170.97 | 18.48 | 0.87 |
| 2 | Screw 2 | 350/450/580 | 22.5/24.5/28 | 70 | 536.89 | 22.66 | 0.61 |
| 3 | Screw 1 | 350/450/580 | 22.5/24.5/28 | 100 | 34.77 | 14.13 | 0.92 |
| 4 | Screw 2 | 350/450/580 | 22.5/24.5/28 | 100 | 15.87 | 10.85 | 0.87 |
| 5 | Screw 3 | 350/450/580 | 22.5/24.5/28 | 70 | 4.00E+10 | 82.7 | 0.91 |
| 6 | Screw 3 | 350/450/580 | 22.5/24.5/28 | 100 | 8377.46 | 32.34 | 0.82 |
| 7 | Screw 4 | 350/450/580 | 22.5/24.5/28 | 70 | 575.94 | 23.35 | 0.89 |
| 8 | Screw 4 | 350/450/580 | 22.5/24.5/28 | 100 | 54.58 | 16.06 | 0.89 |

Additional adaptations of Arrhenius equations were

$$k = k_0 \times \exp\left(-\frac{E_{\text{SMET}}}{\text{SME} \times T}\right) \tag{15}$$

where $k_0$ = preexponential factor (sec), $E_{\text{SME}}$ = SME and temperature constant (whr K/kg) (Figs. 7 and 10) and

$$k = k_0 \times \exp\left(-\left(\frac{E_{\text{SME}}}{\text{SME}} + \frac{E_{\text{T}}}{T}\right)\right) \tag{16}$$

where $k_0$ = preexponential factor (sec), $E_{\text{SME}}$ = SME constant (whr/kg), and $E_{\text{T}}$ = temperature constant (K) (Fig. 8).

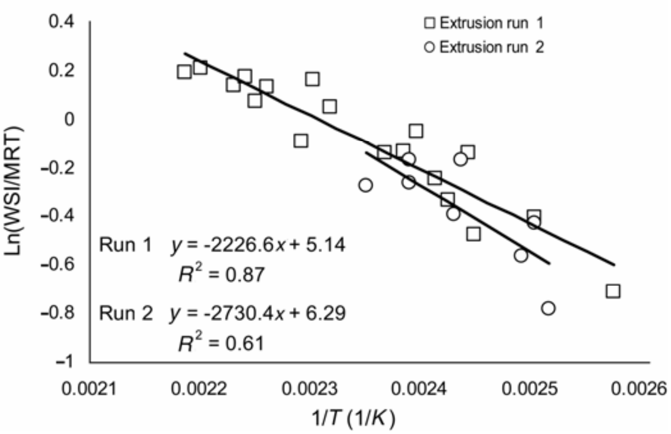

**Fig. 5.** Plots of Arrhenius reaction kinetics for water soluble index (WSI) with extrusion runs 1 and 2.

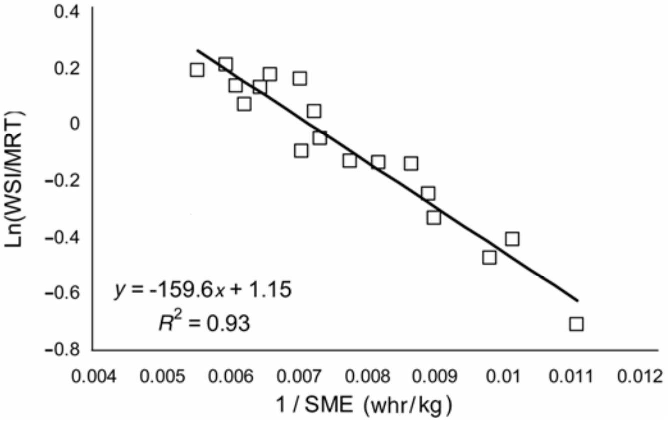

**Fig. 6.** Reaction rate as a function of specific mechanical energy (SME) for water soluble index (WSI) with extrusion run 1.

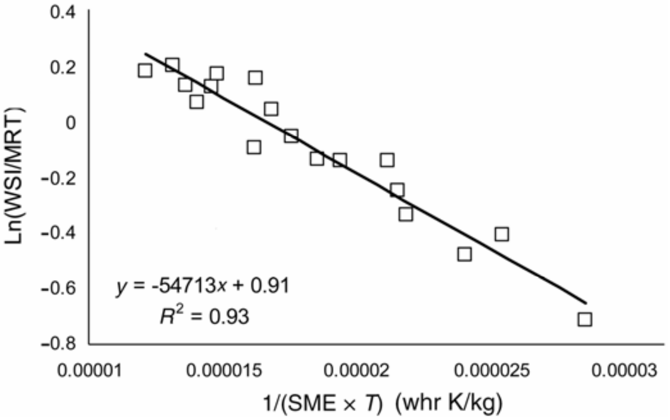

**Fig. 7.** Reaction rate as a function of SME and product temperature for WSI with extrusion run 1.

The experimental results of the WSI of extrudates (extrusion runs 1–8) were used to estimate the parameters of the Arrhenius equation (Equation 13) and the SME model (Equation 14). The results in Table V show that all correlation coefficients were improved with the SME model. WSI during extrusion cooking could be predicted with reasonable accuracy by Arrhenius model and SME model where the rate constant was a function of both

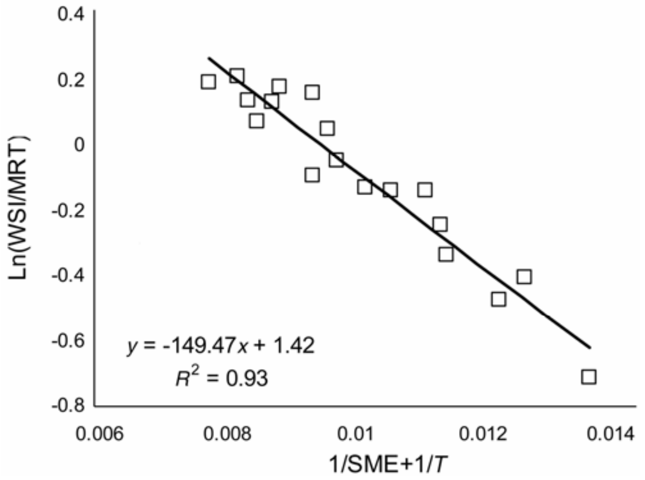

**Fig. 8.** Reaction rate as a function of specific mechanical energy (SME) and product temperature for water solubility index (WSI) with extrusion run 1.

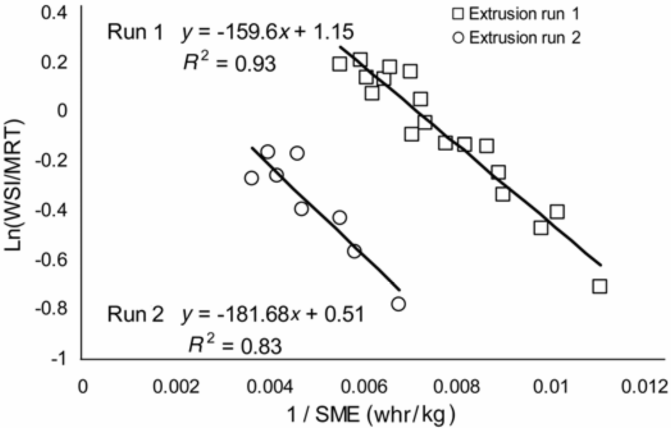

**Fig. 9.** Reaction rate as a function of specific mechanical energy (SME) and product temperature for water solubility index (WSI) with extrusion runs 1 and 2.

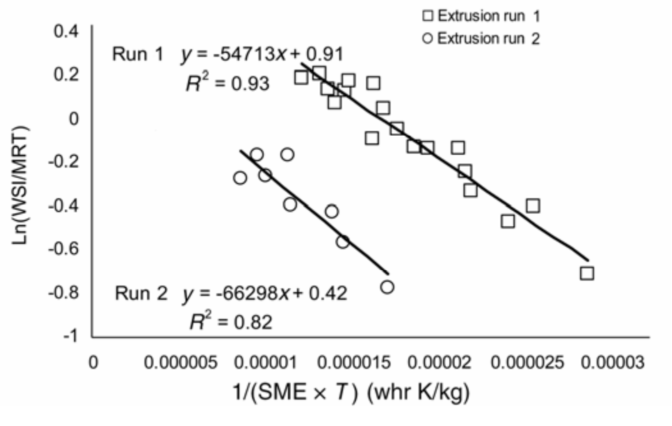

**Fig. 10.** Reaction rate as a function of specific mechanical energy (SME) and product temperature for water solubility index (WSI) with extrusion runs 1 and 2.

**TABLE V**
**Comparison of Arrhenius Model (Equation 13) and SME Model (Equation 14)**

| Extrusion Conditions | | | | | | SME Model | | |
|---|---|---|---|---|---|---|---|---|
| Extrusion Runs | Screw Configuration | Screw Speed (rpm) | Moisture Content (%) | Barrel Temp (°C) | Arrhenius $r$ | $k_0$ (sec) | $E_{\mathrm{SME}}$ (whr/kg) | $r$ |
| 1 | Screw 1 | 350/450/580 | 16.5/18.5/20.5/22.5/24.5/28 | 70 | 0.87 | 3.14 | 159.60 | 0.93 |
| 2 | Screw 2 | 350/450/580 | 22.5/24.5/28 | 70 | 0.61 | 1.67 | 181.68 | 0.83 |
| 3 | Screw 1 | 350/450/580 | 22.5/24.5/28 | 100 | 0.92 | 1.10 | 103.89 | 0.94 |
| 4 | Screw 2 | 350/450/580 | 22.5/24.5/28 | 100 | 0.87 | 1.05 | 57.05 | 0.93 |
| 5 | Screw 3 | 350/450/580 | 22.5/24.5/28 | 70 | 0.91 | 166.78 | 527.62 | 0.97 |
| 6 | Screw 3 | 350/450/580 | 22.5/24.5/28 | 100 | 0.82 | 2.00 | 196.08 | 0.87 |
| 7 | Screw 4 | 350/450/580 | 22.5/24.5/28 | 70 | 0.89 | 1.77 | 234.93 | 0.93 |
| 8 | Screw 4 | 350/450/580 | 22.5/24.5/28 | 100 | 0.89 | 1.06 | 138.49 | 0.92 |

temperature and SME. Twin-screw extrusion technology produces physical and chemical changes in the product through the processes that involve a substantial transfer of energy that plays a major role in the transformation of the material. There are essentially transfers of heat of either a thermal source (from barrel heating and cooling) or a mechanical source (from shearing by movement of the screws). The final quality of the extrudates depends on how the thermal performance of the extruder is controlled and on the thermomechanical history (SME) of the product inside the extruder. The physical meaning of the SME model could be that the WSI rate constant is dependent on mechanical energy. We concluded that WSI is dependent on time, temperature, and mechanical energy. In twin-screw extrusion, the ratio of mechanical to thermal energies varies from 15:1 to 2:1 (Della Valle et al 1989). The reason that the adaptation of Arrhenius equation with SME gave better results than Arrhenius equation alone is that SME models also reflect the major effects of mechanical energies on the WSI.

## CONCLUSIONS

The effects of screw speed, moisture content, barrel temperature, and different screw configurations in a corotating twin-screw extruder on the extrusion system parameters (PT, SME, and RTD) were studied. The results show the effects of extrusion process variables on the properties of the final product, which are characterized by the density, expansion, WAI, and WSI. SME input always acts as one of the key factors on the property changes of extrudates. Moisture content inside the extruder plays an important role in the process control. The most severe treatment for the rice flour occurs with the highest SME, the highest product temperature, and the lowest moisture content. Processing conditions could be optimized for desired properties of final product with the proper value selection of processing variables.

Kinetics of the WSI during extrusion were investigated. The WSI followed a pseudo first-order reaction kinetics. An adaptation of the kinetic model based on the Arrhenius equation has been developed that shows better correlations with SME and distinguishes data from different screw configurations. The rate constant was a function of both temperature and SME. This adaptation of the model improved predictability of WSI, thereby better linking extrusion conditions with extruded product properties.

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