EXPANSION OF THE WHOLE WHEAT FLOUR EXTRUSION

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ABSTRACT

A new model framework is proposed to describe the expansion of extrudates with extruder operating conditions based on dimensional analysis principle. The Buckingham pi dimensional analysis method is applied to form the basic structure of the model from extrusion process operational parameters. Using the Central Composite Design (CCD) method, whole wheat flour was processed in a twin-screw extruder with 16 trials. The proposed model can well correlate the expansion of the 16 trials using 3 regression parameters. The average deviation of the correlation is 5.9%.

INTRODUCTION

Diets with high amounts of whole grains may help achieve significant weight loss, and also reduce the risk of chronic diseases such as diabetes and cardiovascular disease. Epidemiological studies have shown that increased intakes of whole grain products are associated with reduced risks of diabetes mellitus, hypertension, and cardiovascular disease (Jones, 2000, Slavin, 2004, Katcher et al. 2008). However, most cereal products available in Europe and the United States are produced from highly refined grains, which lead to the loss of many potentially beneficial micronutrients, antioxidants, minerals, phytochemicals, and fiber. Subsequently, the consumption of whole grain is far less than the three servings on a daily basis as suggested by the food pyramid of the United States Department of Agriculture (Slavin, 2004). Whole grain breakfast cereals might contribute to satisfy the recommended daily intake, since they fit to the increasingly fast-paced nature of consumer lifestyles. Breakfast cereals are convenient to prepare and easily consumed. In addition, they appeal to consumers of all income levels (Jones, 2000)

Extrusion cooking has become a well-established industrial technology by offering continuous and flexible processes which allow producing breakfast cereals with diverse textures and shapes and ultimately reducing the costs of the final products. The extrusion cooking process can be analyzed in terms of operational parameters, system and product characteristics. By changing the operational parameters it is possible to influence the time-temperature-shear history of the grain flour in the extruder. System parameters such as specific mechanical energy (*SME*) are generally used to describe the time-temperature-shear history, which affects the extent of biopolymer modification and finally the expansion and texture of extruded products. Although starch is known to be the key biopolymer in extrusion cooking, other ingredients of cereal-based food systems such as proteins, fat or fiber also influence the system and product characteristics, e.g. by competing with starch for water (Moraru and Kokini, 2003). Due to these compositional and structural complexities of the raw material as well as the large number of operational parameters involved in the extrusion process, obtaining the desired extrudate properties, e.g. optimal expansion and texture, is a challenging task and often depends on trial and error experience. The empirical experience is often valid only for the specific extrusion equipment that has been used to generate the good operation conditions.

In practical food industrial applications, one often needs to run some trials in a pilot extrusion process in a new food product development stage. Through the trials, a set of specific operating parameters can be established for the new recipe material extrusion. The procedure sometimes is out of control in the time or raw materials cost frame. In this work, we present an engineering procedure to find out the suitable process parameters to reach correct expansion for whole wheat flour extrusion in a pilot plant, which includes experimental design and process parameter correlation.

EXTRUSION EXPERIMENTS DESIGN

The extrusion experiments design was setup by a traditional way. With considering the extruder limitation, a Central Composite Design (CCD) (Esbensen, 2000) was used in the study, which was based on five levels of three variables (Table 1). The independent extrusion variables considered were barrel temperature in different zones, feed water content and screw speed. All other parameters were kept constant. Operating ranges and five standardized levels were established by preliminary study of each variable. According to the CCD, the experimental plan comprised 15 trials (8 factorial points, 6 axial points and 1 central point).

Table 1 Coded levels for the central composite design

Variables	Levels				
	-α	-1	0	1	+α
T_5, °C	101	111	125	139	149
X_w, %	9.2	10.5	12.5	14.5	15.8
N_s, rpm	208	245	300	355	393

In Table 1, T_5 is the temperature of zone 5 (closest zone to die), °C, X_w is the water content, weight percent, %, N_s is the screw speed, rpm, α equals to 1.682.

In the investigation, the extrudate expansion was set as the objective of the extrusion process operation. Through the experiments, it was expected to develop a quantitative correlation for extrudate expansion and extrusion operating conditions. With the help of the correlation model, the number of runs could be reduced for a similar recipe food extrusion using the whole wheat flour.

EXTRUSION EXPERIMENTS

Whole wheat grain was milled to obtain the whole wheat flour. The whole wheat flour was processed in a Werner & Pfleiderer Continua 37 co-rotating twin-screw extruder. The CCD table, i.e. Table 1, was used to set up 15 experimental runs. First, 15 trials were carried out to search the optimal extrusion conditions for maximum expansion. After the 15 trials, one more run was carried out to obtain the maximum expansion. The last trial conditions were estimated from the response surface methodology. The trial capacity was in 22-27kg/hr levels. In the experimental work, the wheat flour, water and additives are directly fed into extruder without pre-mixing. The extrudates were dried at 110°C for about 10 minutes in a continuous processing oven. The extrudate bulk density was measured during the extrusion operations using weight method for 1 liter extrudates.

MODEL CONSTRUCTION

In decades, many investigations have been carried out for the relationship between extrudate expansion and operating conditions (Alvarez-Martinez, et al. 1988, Cai and Diosady, 1993, Moraru and Kokini, 2003). As the food market is very volatile, food producers have to change their recipe all the time. Sometimes the maximum expansion is the target. In other cases, mild extrusion conditions are expected in order to improve the nutritional quality of products (Singh et al. 2007). A quantitative correlation for the extrudate expansion and operating condition will significant benefit the food extrusion applications.

In these correlations and models, some are based on empirical regression from operating conditions (Ding, et al. 2006). Others use the models from a sort of theories or mechanisms (Fan and Mitchell, 1994). In the empirical regressions, a model is often constructed with linear and quadratic terms according the statistical significant for a specific extrusion process. This kind of model construction normally results in many regression coefficients to be determined from experimental data. No doubt, the empirical equation has played an important role in extrusion product development. However, sometimes the empirical models contain many operating parameters and product properties. The uncertainty of the measurement of the product properties could be very diverse. Thus, the uncertainty can transfer into the empirical correlation model. The mechanism model has a solid theoretic background and is the direction to develop a model to describe the extrusion process operation. However, the mechanism-based model often needs accurate food fluids physical property correlations to support its prediction and estimation for the extrusion process behaviors. Because the food fluids belong to non-Newtonian fluid and have very complicated behaviors, the development of a precise physical property calculation model for such food fluid is very difficult.

In this work, a dimensional analysis based model is proposed to correlate the extrudate expansion and extruder operating conditions. Dimensional analysis method is a classical way in industrial applications to setup a model. In the applications of fluid mechanics and fluid heat transfer, the dimensional analysis method has obtained tremendous successful achievements. However, this method is seldom used to setup the correlation between extrudate expansion and extrusion operating parameters.

Extrudate expansion is a reflection of extrusion equipment design and process operation conditions. The equipment design may include different pre-mixing methods, various screw structures, die design, etc. Because the process operation conditions are the adjustable process control parameters for an existing production line, we will only study the correlation between process operation conditions and extrudate expansion in this work. In an extrusion process, many process parameters have influence on the extrudate expansion, e.g. different zone temperatures, die temperature and pressure, process capacity, screw speed, torque, water content, fluid viscosity, specific mechanical energy, etc. Many researchers have used different methods to correlate the process parameters with extrudate expansion (bulk density) and achieved their successes. In this work, the dimensional analysis method will be applied to analysis and correlate these parameters.

Historically, the dimensional analysis methods include the Rayleigh method and the Buckingham pi method (Buckingham, 1914, Rayleigh, 1915, Perry and Green, 1999). In this work, the Buckingham pi method is applied to construct a model. For an extrusion process, we can find out a set of key variables and their dimensions in the engineering system as below:

T_0, T_d=temperature, T
F_T, F_w=flowrate, mass/time, M/t
N_s=screw speed, 1/time, $1/t$
τ=torque, force·length $F{\cdot}L$
P_d =die pressure, force/length^2 F/L^2
$\bar{\rho}_B$ =density, mass/volume, M/L^3

Here, the units T, M, t, F and L respectively represent temperature, mass, time, force and length. Among the variables, $\bar{\rho}_B$ is the bulk density of extrudates, g/liter, F_w is the water flowrate added into the extruder, kg/hr, F_T is the total flowrate of all feed materials (wheat flour, water and additives), kg/hr, T_d is the die temperature, °C, T_0 is the room temperature (25°C), which is also the raw material initial temperature, P_d is the die pressure, bar, τ is the torque, Nm, N_s is the screw speed, rpm.

From the key extrusion process parameters, a variable and units matrix is formed as shown in Table 2.

Table 2 Selected variables and units matrix

Unit	T_0	T_d	F_T	F_w	N_s	P_d	τ	$\bar{\rho}_B$
T	1	1	0	0	0	0	0	0
M	0	0	1	1	0	0	0	1
t	0	0	-1	-1	-1	0	0	0
F	0	0	0	0	0	1	1	0
L	0	0	0	0	0	-2	1	-3

In the formation of Table 2, we assume that the fluid density just before flash-out from die linearly proportions to the bulk density.

Through calculation, it can be found out that the rank of the matrix shown in Table 2 is 5. The physical variables in Table 2 are 8. From the Buckingham pi theorem, three dimensionless groups can be established from the matrix, which are given as follows:

$$\frac{P_d \cdot F_T}{\bar{\rho}_B \cdot \tau \cdot N_s}, \quad \frac{F_w}{F_T}, \quad \frac{T_d}{T_0}$$

In the studied extrusions process, the term F_w/F_T represents the water content of processing materials. The term T_d/T_0 is the temperature changes of processing materials from its initial condition to the vicinity of flash-out from extruder. The term $\frac{P_d \cdot F_T}{\bar{\rho}_B \cdot \tau \cdot N_s}$ represents the energy added into the processing materials. In fact, the term $\tau \cdot N_s/F_T$ reflects the widely used specific mechanical energy (SME). From the three dimensionless groups, different model expressions can be constructed. In this work, a model is obtained as

$$\bar{\rho}_B = K(X_W)^{\alpha}\left(\frac{T_d}{T_0}\right)^{\beta}\left(\frac{P_d \cdot F_T}{\tau \cdot N_s}\right) \qquad (1)$$

where $\bar{\rho}_B$ is the bulk density of extrudates, g/liter, X_w is the water content of feed material and equals to F_w/F_T, weight fraction. *K*, α and β are the model coefficients, which need to be determined from experimental data.

From the equation (1), it can be seen that the equation lacks of physical properties of food fluids. Thus it is only suitable to the specific whole wheat flour extrusion. However, the equation is simple and contains only correlation coefficients. The simple format model meets the engineering applications.

Using the data from the 16 runs for whole wheat flour extrusion, the model coefficients are determined as shown in Table 3. The average absolute deviation (AAD) of the model correlation with experimental bulk density data is 5.9%, where AAD is calculated as.

$$\text{AAD} = \frac{1}{n}\sum_n \left[\frac{\bar{\rho}_B^{\text{exp}} - \bar{\rho}_B^{\text{cal}}}{\bar{\rho}_B^{\text{exp}}}\right]\% \qquad (2)$$

In equation (2), n is the number of experimental runs. The model correlation results for the extrudate bulk density are shown in Figure 1. The estimation error distribution of the model for extrudate bulk density is shown in Figure 2. As shown in Figure 2, the bulk density estimation errors are evenly distributed.

Table 3 Coefficients of equation (1)

Coefficient	*K*	α	β
Value	13508	0.7774	-0.2882

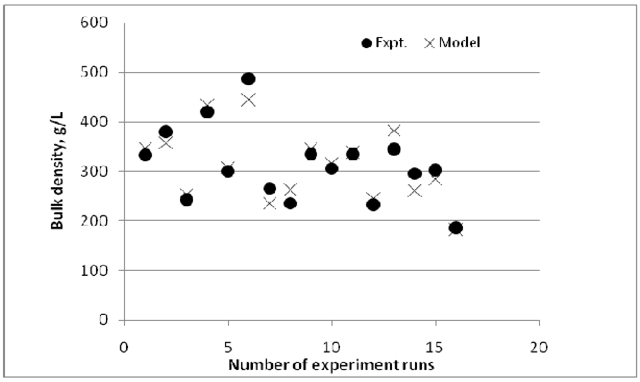

Figure 1: Correlation results of bulk density at different runs

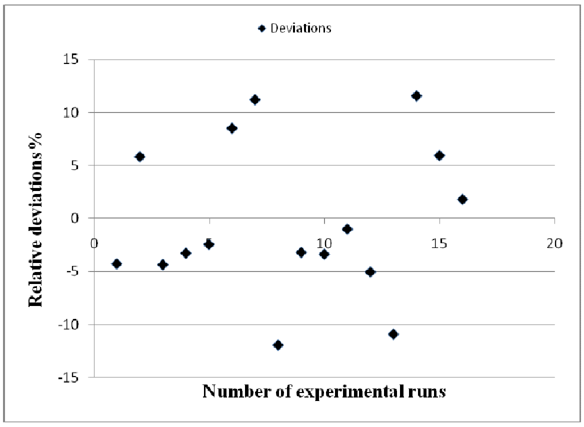

Figure 2: Relative deviations of equation (1) in correlation with bulk density and extusion operating conditions

In Figure 2, the relative deviation (R_d) is calculated as

$$R_d = \frac{\bar{\rho}_B^{\text{exp}} - \bar{\rho}_B^{\text{cal}}}{\bar{\rho}_B^{\text{exp}}}\% \qquad (3)$$

DISCUSSIONS AND CONCLUSIONS

In engineering applications, a simple and reliable model often can help engineers to reach an optimal solution through observing the interactions of different operational parameters. In this work, the model construction is based on the engineering principle. A dimensional analysis method is used to build a model with the key process parameters. From the model one can quantitatively estimate the extrudate bulk density changes with different control parameters and the interactions of these parameters.

The model estimation results show that the proposed can successfully represent the extrudate bulk density in different extruder operating conditions. The average absolute deviation in the estimation of extrudate bulk density is 5.9%.

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