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The effects of screw configuration on the screw fill degree and special mechanical energy in twin-screw extruder for high-moisture texturised defatted soybean meal

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ABSTRACT

To control the mechanical energy output by adjusting the screw configuration during soybean protein extrusion texturisation, the relationship between the screw configuration and the special mechanical energy was investigated. Different types of screw elements, element lengths and positions were designed and configured, while the other parameters were kept unchanged. The screw fill degree and specific mechanical energy output were detected. The results demonstrate that when the helix angle of conveying elements turns from forward (45°) to reverse (−37.5°), the disc width of the kneading elements decreases from 7.5 mm to 5 mm, and when the disc stagger angle turns from forward (45°) and forward (90°) to reverse (−45°), the screw fill degree and specific mechanical energy increase. When the length of the reverse kneading element increases, the screw fill degree and specific mechanical energy increase. When the distance between the reversing knead element and the die increases or the element space between the reversing knead element increases, the specific mechanical energy appears to decrease. Thus, the elements with reverse helix or stagger angles, narrow kneading disc, long length and flow-restricting ability increase the screw fill degree and induce high special mechanical energy. The special mechanical energy increases when the reverse kneading element is located at the screw position where the material viscosity is relatively high during extrusion.

1. Introduction

Extrusion has become an important processing technique in increasingly varied food processes (Harper and Clark, 1979). As a continuous efficient cooking, mixing and forming process, extrusion has been increasingly used to produce breakfast cereals, baby foods, flat breads, snacks, meat and cheese analogues, and modified starches. Despite the increased use of extrusion technology, the extrusion process remains a complicated multi-input–output system to be mastered (Ding et al., 2006).

A simplified system analysis model has been proposed, which categorises extrusion parameters into three groups: process parameters, system parameters and product properties. Among these three types of parameters, the process parameters affect the properties of the final products by affecting the extrusion system parameters (Chen et al., 2010; Meuser et al., 1984; Onwulata et al., 1994). Independent variables, such as the temperature, screw speed, screw configuration and die geometry, result in system parameters, such as the mechanical and thermal energy inputs and the residence time. These intermediate parameters induce reactions that affect the product attributes. Twin-screw extruders enable greater flexibility of operations to control the product attributes by monitoring a desired time, temperature and shear history because of the addition of independent variable screw configuration (Choudhury and Gautam, 1998). The screw configuration is a key factor that affects the product transformation, residence time distribution, degree of fill and energy inputs to the material (Gautam and Choudhury, 1999a).

The screw is the principle component of a food extruder. The screw accepts the material at the inlet, conveys, mixes, and forces the material through the die at the discharge (Harper and Clark, 1979). Twin-screw extruders use segmented designs, which provide the flexibility to alter the screw geometry. Extruder screws can be built from different types of conveying and mixing elements (kneading and reverse screw elements). The kneading elements are mild flow-restricting elements and individually have no conveying effect. However, the elements can combine and orient to cause

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static mixing and/or weak forward or backward conveying. The reverse screw elements are characterised by a reverse flight that pushes the material backward (Kollengode et al., 1996). The arrangement of different characteristics of the screw elements (pitch, stagger angle, length) in different positions and spacing determine screw profile/configurations is the main factor that influences the performance (product transformation, residence time distribution, mechanical energy input) during the extrusion processing (Choudhury and Gautam, 1998).

For the screw configuration, if the longer reversed screw element is placed or the screw is placed closer to the die, the starch breakdown increases (Barres et al., 1990; Colonna et al., 1983). Furthermore, the starch breakdown, mechanical energy input and water solubility index systematically increase when the mixing elements are moved farther from the die, longer elements, and spaced with increased spacing among the elements (Gautam and Choudhury, 1999b). The incorporations of the reversed screw element, kneading element and mixing elements increases the specific mechanical energy, expansion ratio and water solubility index (Choudhury and Gautam, 1998; Gogoi et al., 1996). Severe screw configuration produced more expanded product with low bulk density than that of medium screw configuration (Altan et al., 2009).

The special mechanical energy (SME) is the amount of work input from the driver motor into the raw material that is extruded, which provides a good characterisation of the extrusion process (Godavarti and Karwe, 1997). The SME is also an important parameter that affects the final product characteristics, such as the solubility, density, expansion index, and hardness. The SME values indicate the extent of molecular breakdown or degradation that the material undergoes during the extrusion process (Einde et al., 2005; Fang et al., 2013, 2014; Gropper et al., 2002; Owolabi et al., 2008). Evidently, the same energy input produces similar changes in starch properties, which enables the comparisons of the operating conditions of two different co-rotating twin-screw extruders with screw diameters of 37 and 120 mm (Meuser et al., 1984).

Regrettably, the relationship between the SME and the screw configuration is not clear, particularly during the vegetable protein extrusion. The objective of this study is to investigate the effects of the screw configurations, such as the length, position of the screw elements, and space between them on the SME during high-moisture texturised defatted soy meal.

2. Materials and methods

2.1. Materials

Defatted soy meal was obtained from Shandong Yuwang Industrial Co., Limited and used as the main feed material for all experiments. The components are presented in Table 1.

2.2. Extruder

A pilot-scale, co-rotating, intermeshing, twin-screw food extruder (Brabender GmbH and Co., Germany) was used. The diameter of the screw was 25 mm, and the Length to Diameter (L/D) was 20. At the end of the extruder, a slit die ($2 \times 20 \times 100$ mm) was attached. The barrel was segmented into five temperature-controlled zones, which were heated using an electric cartridge heating system and cooled with running water. The extruder response, which included the motor torque and die pressure, were automatically recorded on-line at a frequency of once per 10 s.

Table 1
Proximate composition of defatted soybean flour %.

Components	Mean
Moisture	8.33
Protein	53.99
Fat	0.52
Ash	6.05
Crude fibre	2.51
Nitrogen soluble index	81.6

2.3. Extrusion conditions

The feeder was calibrated to determine the set point of the rotary feeder switch for defatted soy meal to obtain a flow rate of 2.4 kg/h for all experimental runs. The screw speed and moisture content were fixed at 120 rpm and 45%, respectively. The temperature profiles in the 5 barrel sections from the feed to the die end were set at 60, 120, 148, 137, and 70 °C for all experiments.

2.4. Screw configuration

The extruder screw was divided into two zones: experimental and non-experimental zones. The configuration was maintained constant in the 300 mm long non-experimental zone. The screw profile in this section from the feed end was denoted with the code of CE/37.5/37.5/8, which represented the element type/element length (mm)/helix angle (°)/element number. CE denoted the conveying element.

In total, 21 screws with different element types and element locations in the 200 mm experimental zone were studied (Fig. 1). The screw configuration parameters were shown at Table 2. The element type included two types of conveying elements (CE), five types of kneading elements (KE) and one type of gear element (GE).

Screw No.1 was built with only CE/25/45, which represented a conveying element with 25 mm length and 45° helix angle in the 200 mm experimental zone, which was referred to as CK. Screws No. 2-15 were built to study the position effects of KE/25/−45, which represented a kneading element with 25 mm length and −45° stagger angle, by replacing 25 mm or 50 mm CE/25/45 at different locations in the 200 mm experimental zone. Screws No. 16-21 were built to study the element type effect of KE/25/−45, KE/37.5/45, KE/37.5/90, KE/37.5/−45, GE/25, and CE/12.5/−37.5 by replacing 75 mm CE/25/45 at 50 mm from the die.

2.5. Screw fill degree (SFD)

The screw fill degree (SFD) was calculated by measuring the screw volume difference between before and after the extrusion. The screw volume was measured using the water replacement method. The screw was put into a container with certain water content, and the water was replaced, collected and weighed. The weight of the replaced water represents the screw volume. The screw was pulled out from the extruder when the extruder reached steady state and completely stopped. Then, the screw volume after the extrusion was measured.

2.6. Specific mechanical energy (SME)

The specific mechanical energy (SME) was calculated using the screw speed n (120 rpm), motor torque T (Nm, automatically recorded using a computer) and mass flow rate (MFR) (g/min, which determines the output of the extrudate within 3 min) based on the following formula (Fang et al., 2014; Godavarti and Karwe, 1997).

$$\mathrm{SME(kJ/kg)} = \frac{2\pi \times n \times T}{\mathrm{MFR}}$$