LWT - Food Science and Technology 79 (2017) 213–222

Contents lists available at ScienceDirect

LWT - Food Science and Technology

journal homepage: www.elsevier.com/locate/lwt

Residence time distribution and flow pattern of reduced-gluten wheat-based formulations in a twin–screw extruder

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ARTICLE INFO

Article history:
Received 19 August 2016
Received in revised form
6 January 2017
Accepted 8 January 2017
Available online 9 January 2017

Keywords:
Wheat-based formulation
Extrusion
Processing condition
Residence time distribution
Flow pattern

ABSTRACT

Residence time distribution (RTD) and flow pattern in a co-rotating twin screw extruder were evaluated using a color tracer method. A reduced-gluten formulation was prepared by mixing wheat flour, sesame protein concentrates and Tef flour in the proportion of 50:20:30, respectively. The effects of screw speed (150, 180 and 220 rpm), feed moisture content (17, 19 and 21 g/100 g wet basis) and feed rate (40 and 90 g/min) on RTD and flow pattern were investigated. All tested conditions were found to have a significant ($P < 0.05$) effect on the mean residence time and other RTD parameters. Higher screw speed, higher moisture content and higher feed rate resulted in shorter mean residence times and lower RTD spread due to enhanced barrel fill, mass flow rate and system pressure. A dispersion number was used to define the level of axial mixing in the extruder and, as defined, the axial mixing was more influenced by the feed rate than screw speed. Increasing feed rate resulted in the mixing pattern to become more like plug flow, whereas, mixed flow condition achieved when the screw speed was increased. Feed moisture had no significant effect on mixing pattern.

1. Introduction

Extrusion cooking is a prominent food processing operation in which processing conditions and raw ingredient profiles have an influence on intermediate processing conditions and product qualities (Omeire, Iwe, & Nwosu, 2013). Residence time is an important process parameter that controls the extent of reaction (Alam, Kaur, Khaira, & Gupta, 2016). Residence time distribution (RTD) indicates the distribution of time that solid or fluid material's stay inside a continuous flow system. It has a direct influence on the product quality by characterizing the reaction time, temperature and shear treatment level of the process (Yu, Meng, Ramaswamy, & Boye, 2014). RTD also gives information about the degree of mixing, velocity profile, mass flow and the life expectancy of fluid elements during their passage through the extruder (Reitz, Podhaisky, Ely, & Thommes, 2013).

Residence time distribution is characterized by two main parameters: the mean residence time and the exit age distribution of the material in the extruder. It is significantly affected by processing conditions such as feed moisture, screw speed and feed rate (Kumar, Ganjyal, Jones, & Hanna, 2008; Yu et al., 2014).

Non-ideal mass flow distributions in flow processes can be explained using RTD (Levenspiel, 1999). The RTD is usually described by the age distribution of a material in an extruder, E (t), and exit age over time, F (t), of a fluid leaving a vessel. This is achieved as a result at the die exit to a pulse tracer (color dye) introduced at $t = 0$ at some part of the reactor. The dye concentration in the extrudate (C_i) is measured either by spectrophotometry or colorimeter and calculates C_i from the established color values versus the dye concentrations standard curve (Lee, 2012). It is required to normalize the tracer concentrations at each point in

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http://dx.doi.org/10.1016/j.lwt.2017.01.015
0023-6438/

time by dividing them by the total amount of tracer passing through the system. Thus, E(t) curve can be obtained by the following equation (Levenspiel, 1999):

$$E(t) = \frac{C(t)}{\int_0^\infty C(t)dt} \cong \frac{C_i}{\sum_{i=0}^{\infty} C_i \Delta t_i} \tag{1}$$

where C is the tracer concentration at time t.

The F(t)-curve is interrelated to the E(t)-curve and it represents the cumulative distribution function in the exit stream at any time. It is given by

$$F(t) = \int_0^t E(t)dt \cong \frac{\sum_0^t C(t)\Delta t_i}{\sum_0^\infty C(t)\Delta t_i} \tag{2}$$

Application of mean residence time (t_m) and its variance (σ^2) are also important parameters of RTD (Yu et al., 2014). The particle mean residence time, t, is defined by the following mathematical expression (Levenspiel, 1999):

$$t_m = \int_0^\infty tE(t)dt = \frac{\int_0^\infty C(t)tdt}{\int_0^\infty C(t)dt} = \frac{\sum_{i=0}^\infty t_i C_i \Delta t}{\sum_{i=0}^\infty C_i \Delta t} \tag{3}$$

The variance, which represents the square of the spread of distribution, is calculated by the following equation (Levenspiel, 1999):

$$\sigma^2 = \sum_{i=0}^{\infty} (t_i - t_m)^2 \, E(t_i) \tag{4}$$

All values of particle residence times can be normalized by dividing the individual residence times by the mean residence time to compare the flow pattern of different processing conditions relative to each other (Kumar et al., 2008). Since it is common to plot residence time distributions in a normalized form, the normalized time, E and F curves are obtained as follows (Levenspiel, 1999):

$$\text{Since} \quad \theta = \frac{t}{t_m} \tag{5}$$

The plots can be normalized as follows

$$E(\theta) = \frac{C_\theta}{C_0} = \frac{C_\theta}{\sum_{\theta=0}^\infty C_\theta \Delta t} = t_m \times E(t) \tag{6}$$

$$F(\theta) = \int_0^t E(\theta)d\theta = \frac{\sum_0^\theta C(\theta)d(\theta)}{C_0} = \frac{\sum_{i=0}^\theta C_i \Delta\theta}{\sum_{i=0}^\infty C_i \Delta\theta} = F(t) \tag{7}$$

$$\sigma_\theta^2 = \frac{\sigma^2}{t_m^2} \tag{8}$$

Since mixing in the extruder is mostly undertaken by laminar shearing action, it is difficult to quantify the axial mixing directly from RTD curves. The dispersion number is a good index for axial mixing in an extruder (Kumar, Ganjyal, Jones, & Hanna, 2006). The dispersion number (D_N) defined as D/uL, where D is the diffusivity, u is the flow rate and *L* is the length of vessel, is the reciprocal of Peclet number used to measure the extent of axial dispersion (Kumar et al., 2006). When D_N approaches zero, the dispersion is negligible and hence the flow is plug flow. As D_N approaches infinity, there exists significant dispersion and hence the flow is mixed flow. In a closed vessel, the value of D_N can be calculated from the mean residence time and variance of the curve by:

$$\sigma^2{}_\theta = \frac{\sigma^2}{t_m{}^2} = 2\frac{D}{uL} - 2\left(\frac{D}{uL}\right)^2 \left(1 - e^{-\frac{uL}{D}}\right) \tag{9}$$

The RTD and axial mixing behavior of wheat flour, Tef flour and sesame protein concentrate formulations during twin-screw extrusion processing has not been previously studied. The objective of this work was therefore to determine the effect of processing conditions such as feed rate, feed moisture and screw speed on the on the RTD and axial mixing behavior (D_N) of wheat flour, Tef flour (Eragrostis Tef) and sesame protein concentrate formulations. RTD has been recognized as an important parameter to understand the flow behavior of feed mixes through the extruder. The final product is aimed as a functional breakfast cereal of relevance to African/Ethiopian region. It is prepared as a value added product to replace the traditional high carbohydrate based cereal foods. This formulation cereal product is rich in protein and fiber as well as low in gluten and carbohydrate compared to traditional starch based formulations. Moreover, correlating RTD curves and D_N with processing conditions helps in further scale up of the process.

2. Materials and methods

2.1. Experimental materials

A wheat variety (*Triticum aestivum)* used for bread making, namely Hidase, was obtained and Tef (*Eragrostis Tef*) variety namely Kuncho were obtained from Kulumsa Agricultural Research Center (KARC) and Debre Zeit Agricultural research center (DZARC) respectively, which are part of federal centers under Ethiopian Institute of Agricultural Research (EIAR). Hulled sesame grain (*Sesamum indicum* L.) was obtained from Select Hulling PLC (Addis Ababa, Ethiopia).

2.2. Materials preparation

Mature and unbroken wheat kernels and Tef grains were selected and washed to remove the dirt. Tef grains were placed in a solar dryer to dry. Wheat grains were immersed in plenty of distilled water to condition them for about 20 min and then drained. The wet grains were then pounded to loosen the outer pericarp, solar dried and pounded again to separate the hull from the endosperm. The hulled and dried wheat grains and dry Tef grains were milled separately using a laboratory scale cyclone mill (Foss Tecator, Höganäs, Sweden) and passed through a 0.5 mm aperture sieve. The flours were packed in polyethylene bags and kept in a refrigerator until further use.

Oil from hulled sesame seed was extracted using a small-scale oil expeller. The cake was defatted by immersing first in n-hexane and then in petroleum ether consecutively for 12 h in each solvent with continuous mixing, then drained from the solvents and oven dried at 65 °C overnight (12 h). The protein concentration was done using an aqueous-alcohol process (Berk et al., 1992). The process was based on the ability of aqueous solution of ethanol to extract the soluble sugar fraction. The defatted sesame flour was immersed in a 70% aqueous ethanol solution (100 g of defatted sesame flour in 300 ml alcohol solution) and stirred intermittently for 3 h. The solution was then drained to obtain sesame paste. The paste was then oven dried at 60 °C overnight (12 h) to obtain sesame protein concentrate. Dried sesame protein concentrate (SPC) was milled using laboratory scale cyclone mill (Foss Tecator, Höganäs, Sweden) and passed through 0.5 mm aperture sieve. The