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Numerical study of the extrusion process in cereals production: Part I. Fluid-dynamic analysis of the extrusion system

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Abstract

A numerical investigation on the extrusion cooking process for cereals in a co-rotating twin-screw extruder was carried out, using a fluid-dynamic, numerical simulation model. Simulation tests were carried out, varying temperature, screw rotation velocity, mass flow rate and extruder geometry. Fluid-dynamic parameters inside the extruder, as shear rate, residence time and mixing index were evaluated.

Extruder geometry is an important parameter in the extrusion process, since it affects the values of shear rate and residence time and consequently the quality of the final product. Screw with regular geometry shows a more regular profile of the mean shear rate along the extruder, but characterized by lower values of this parameter, determining a reduced gelatinization of the compound. Instead, extruders characterized by a more complex geometry allow to obtain higher values of shear rate, but with some difficulties in the control of the final quality of the products due to a more complex behavior of the shear rate profile along the screw axis.

Keywords: Extrusion; Cereals; Simulation; Fluid-dynamic analysis

1. Introduction

Extrusion cooking of cereals is a very important process in food industry, since it regards a wide range of products, as snack-foods, baby-foods, cereals for breakfast and pasta. Extruders minimize the operating costs and rationalize the productive process, combining energetic efficiency and versatility. Nevertheless, the rheological properties and the fluid-dynamic behavior of food compounds make extrusion cooking a very complex process.

Screws, mixing paddles, external barrel and final die are typical components of a twin-screw extruder. Screws and mixing paddles play the most important role in the extrusion process, since they transport, mix, cut and stretch the cereals inside the extruder (Singh, Smith, & Frame, 1998). The external barrel contains the material flow and acts like a heat exchanger to cook the food compound; as a final point, the die shapes the final product (Senanayake & Clarke, 1999).

An extruder is a bioreactor that transforms the cereals, under high temperature and pressure. As hydrated powder, the crude material feeds the extruder, undergoing chemical and physical transformations (cooking process) because of the thermal effects and the shear stress (Chiruvella, Jaluria, & Karwe, 1996).

Although all cereals contain meanly the same fundamental chemical elements, as starch, proteins, lipids and semolina, during the extrusion their behavior is different according to their chemical composition. During the extrusion, mechanic shear forces, generated by screws and mixing paddles, fragment the cereal molecules,

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Nomenclature

σ_{ij}	stress tensor of a moving fluid (Pa)	K_n	constant
$p\delta_{ij}$	isotropic part of stress tensor (Pa)	m	constant
T_{ij}	extra-stress tensor (Pa)	T	temperature (°C)
d_{ij}	rate-of-strain tensor (1/s)	RTD	residence time distribution
u_{ij}	velocity (m/s)	$\dot{\gamma}$	shear rate (1/s)
C	moisture (%)	η	viscosity (Pa s)
F_i	volumetric force (N/m^3)	ρ	density (kg/m^3)
K	consistency (kPa s^m)	λ	mixing index
K_m	constant	ω	magnitude of the vorticity vector (1/s)

producing carbohydrates with light molecular weight. Gelatinization process of wheat starch takes place fully inside the cooking zone, with less intensity near to the final die of extruder. These transformations can be described through mechanical degradation models (Cai, Diosady, & Rubin, 1995).

In the extrusion process, the characteristics of final products are strongly influenced by screw rotation velocity and temperature (Guha, Ali, & Bhattacharya, 1997): these parameters can be modified during the process, improving the quality of final products (Bhattacharya, 1997).

Previous experimental tests showed the influence of some parameters, as hydration, temperature and screw rotation velocity, on the flow pressure and the quality of final product. Under rheological aspects, the hydrated durum wheat semolina was characterized through the friction coefficients and the compressibility curves (Le Roux & Vergnes, 1995).

Geometric characteristics of final die (diameter and length) play an important role in the extrusion process, since they influence the expansion of extruded product (Bouzaza, Arhaliass, & Bouvier, 1996).

In this study, numerical simulations of the extrusion for cereals in a co-rotating twin-screw extruder were carried out to investigate the fluid-dynamic behavior of the system. The relationship between the working conditions, as temperature, mass flow rate, screw geometry, rotation velocity and the fluid-dynamic parameters, as shear rate, residence time and mixing index, that affect the extruded product quality, has been analyzed using a numerical simulation model.

2. The twin-screw extruder

Two screws with mixing paddles constitute the main part of a typical co-rotating twin-screw extruder (Fig. 1). The screws transport the food compound inside the barrel toward a die to perform the final extrusion (Senanayake & Clarke, 1999).

Unlike single screw extruders, twin-screw extruders consent to mix, to cut and to stretch the food compound thanks to the mixing paddles, then modifying the alimentary characteristics of final product, as gelatinization grade and digestibility. In the extruders, the temperature

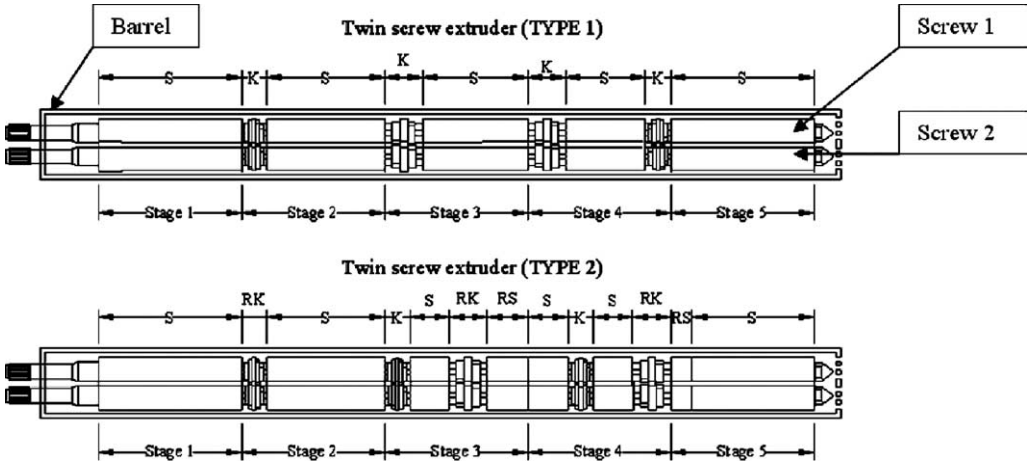

Fig. 1. Geometry of extruders Types 1 and 2 (S = screw; RS = reverse pitch screw; K = kneading in the mixing paddles zone; RK = reverse kneading in the mixing paddles zone).