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Influence of medium-chain triglycerides on expansion and rheological properties of extruded corn starch

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ABSTRACT

Enhancement of product properties of extruded starch based products can be achieved by incorporating health promoting oil into the matrix. In order to achieve a preferably high expansion with a homogeneous pore structure, the expansion mechanisms have to be understood. In our study, we applied a customized twin-screw extruder set up to feed medium-chain triglycerides after complete gelatinization of corn starch, minimizing its effect on the starch gelatinization. Despite the fact, that the addition of up to 3.5% oil showed no influence on the extrusion parameters, we observed a three-fold increase in sectional expansion. Longitudinal expansion was less affected by the oil content. Rheological properties of the gelatinized starch were measured using an inline slit die rheometer. In addition to shear viscosity, we presented a method to determine the Bagley pressure, which reflects the elongational properties of a fluid. We were able to observe an increase in the Bagley pressure from about 25 bar up to 35–37 bar due to the addition of oil.

1. Introduction

Extrusion cooking of starch based matrices is a common process in cereal or snack manufacturing. Important product quality attributes are texture and crispness, which depend on the expansion of molten starch during extrusion cooking. By incorporation of health promoting ingredients into directly expanded products, additional benefits can be generated. Bioavailability and accessibility of the incorporated additives are important product properties to be addressed. In the case of lipophilic bioactive components, e.g. phytosterols and carotenoids, bioavailability can be increased by encasing them in a lipophilic carrier e.g. vegetable oil (Horn, 1989; Ribeiro et al., 2006). Dispersion of the lipophilic carrier into small droplets improves the solubility, and leads to further enhancement of bioavailability and stability (Ribeiro, Schuchmann, Engel, Briviba, & Walz, 2009). Therefore, the extrusion process must be designed such that lipophilic carriers are efficiently mixed into the molten starch based matrix without adversely affecting the final product quality attributes, such as texture. However, incorporation of oil into extruded products is reported to significantly change the expansion, which plays a crucial role on texture (Faubion & Hoseney, 1982; Lin, Hsieh, & Huff, 1997; Singh & Smith, 1997). The mechanisms behind this phenomenon have not yet been identified. To enable the manufacturing of health promoting extruded foods with the desired texture and crispness, understanding the expansion behavior of oil-loaded starch melt is crucial.

Recently, the role of rheological properties in water-vapor induced expansion of melted starch, and the related challenges in this field was reviewed by Moraru and Kokini (2003). Kokini, Chang, and Lai (1992) developed a simple model correlating the ratio of vapor pressure and melt viscosity with sectional expansion. Alvarez-Martinez, Kondury, and Harper (1988), Della Valle, Vergnes, Colonna, and Patria (1997) and Launay and Lisch (1983) suggested that sectional expansion mainly depends on the elastic properties of the matrix, while longitudinal expansion is influenced by viscous properties. Another parameter influencing expansion is the elongational viscosity, which can be related to the elastic properties of the material (Pai, Blake, Hamaker, & Campanella, 2009). In polymer foam processing, expansion is often correlated to the elongational behavior of the polymer melt, since bubble growth leads to biaxial extension of the surrounding matrix (Micic, Bhattacharya, & Field, 1998; Munstedt, Kurzbeck, & Kaschta, 1996). However, measurements of the elastic properties as well as of the elongational viscosity of a molten starch matrix remain a challenging task. Several authors applied exit-pressure or hole-pressure methods to evaluate the elastic properties of starch matrices

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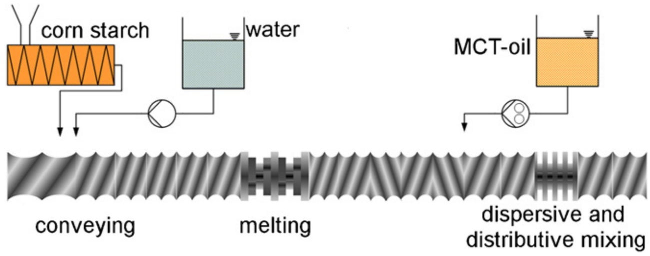

Fig. 1. Setup of the extruder, the screw geometry and feed locations of corn starch, water and MCT-oil.

(Baird, 2008; Padmanabhan & Bhattacharya, 1991). The limitations of these methods were widely discussed by Bhattacharya and Padmanabhan (1994). Bagley (1961) proposed to use the extra pressure loss occurring at the entrance and the exit of a die due to elongational flow as a measure for elastic properties. As a result, some authors developed methods to correlate the so-called "Bagley pressure" to the elongational viscosity or to the first normal stress difference (Cogswell, 1972; Gleissle, 1988).

The aim of this study is to examine the influence of medium-chain triglyceride oil content on the rheological properties and the expansion behavior of molten corn starch. Special effort was given to characterize the elastic behavior of the matrix and deduce the correlation between its rheological properties and expansion characteristics.

2. Materials and methods

2.1. Materials

Commercially available native corn starch *C*Gel 03401* at moisture content of 10% (wet basis) was obtained from *Cargill, Germany*. Medium-chain triglycerides (MCT-oil) mainly consisting of caprylic and capric acid triglycerides with chain length of 8 and 10 carbons, respectively, were ordered from *Schumann & Sohn*, Germany.

2.2. Methods

2.2.1. Setup of extrusion trials with oil injection and inline-rheometer

Extrusion trials were performed with a co-rotating twin-screw extruder (*Coperion Werner & Pfleiderer ZSK 26Mc*) with a screw diameter of 25.5 mm. The extruder barrel has an overall length of 749 mm (barrel length to diameter ratio is 29) and is divided into 7 sections. Corn starch and water were fed into the first barrel by a gravimetrically controlled feeder (*Brabender DDW-DDSR 40*) and a water feed pump (*TrueDos, Alldos Eichler GmbH, Pfinztal, Germany*), respectively. MCT-Oil was added in the fifth barrel via a piston metering pump. Screw geometry was designed to (i) mix corn starch and water homogeneously at the inlet by conveying elements with increasing pitch, followed by 45° mixing elements, (ii) melt the mixed starch based dough completely in a stagnant area generated by reverse elements and (iii) achieve a good dispersive and distributive mixing of oil into the molten starch based matrix by using 2 kneading elements (see Fig. 1). Between the outlet of the extruder and an extruder die, an inline-rheometer was mounted.

The extruder was operated at constant corn starch feed rate $\dot{Q}_{corn}$ of 10 kg h^{-1}, water flow rate $\dot{Q}_{water}$ of 1 kg h^{-1} resulting in a total moisture content of 18% (wet basis). The screw speed was 500 rpm in all experiments. Oil feed rate $\dot{Q}_{oil}$ was varied to have oil contents of 0%, 0.8%, 1.7% and 3.5% (wet basis) in the extruded product. Each of the 7 extruder barrel sections, except the first one, was heated separately to 60 °C, 80 °C, 100 °C, 100 °C, 100 °C and 100 °C, respectively.

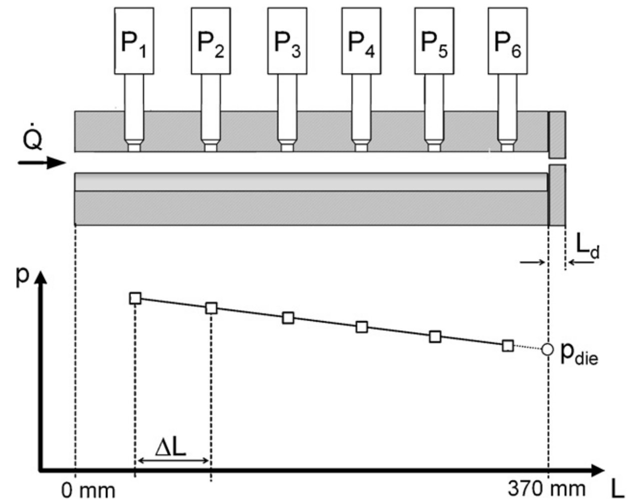

Fig. 2. Rheometer setup with pressure transducers and the corresponding measured pressure values along the slit channel. The total die pressure loss p_{die} is determined by linear extrapolation.

2.2.2. Inline-rheometer and evaluation of rheological properties

The rheometer consisted of a single slit channel. The volumetric flow rate $\dot{Q}_{melt}$ could be determined directly from the mass flow rate in the extruder. Melt density was calculated by additive rule, assuming a dry corn starch density of 1450 kg m^{-3} (Vergnes, Della Valle, & Tayeb, 1993) and water density of 1000 kg m^{-3}. Due to the low amount of oil compared to starch and water, the density of MCT-oil was neglected (estimated error max. 1.3%). The slit channel had an overall length of 370 mm, a height of H = 10 mm and a width of W = 15 mm. The shear rate was calculated by Eq. (1).

$$\dot{\gamma}_{app} = \frac{6 \cdot \dot{Q}_{melt}}{W \cdot H^2} \quad (1)$$

The rheometer was heated to 150 °C and temperature was kept constant during the experiments by an electric heating jacket. The melt temperature was measured by a temperature transducer positioned midway of the slit channel. The pressure along the channel was measured by 6 flush-mounted pressure sensors (*Gefran melt pressure sensor, M3 series*, max. pressure 2 × 500 bar, 2 × 200 bar, 2 × 100 bar). From the pressure drop between two pressure sensors ΔP the shear stress τ (Pa) could be calculated using Eq. (2).

$$\tau = \frac{\Delta P \cdot H}{\Delta L \cdot 2} \quad (2)$$

ΔL is the distance between two pressure sensors (mm) and H is the slit height (mm). Then the apparent shear viscosity η_{app} (Pa s) was calculated using Eq. (3).

$$\eta_{app} = \frac{\tau}{\dot{\gamma}_{app}} \quad (3)$$

At the outlet of the rheometer, an orifice die with a diameter d_{die} = 3 mm was mounted. To determine the pressure directly before this orifice die, the total die pressure loss p_{die}, the pressure measured along the channel was extrapolated (see Fig. 2). p_{die} is defined as $p_{die} = p_{entrance} + p_{viscous} + p_{exit}$ where $p_{viscous}$ is the pressure loss due to viscous dissipation inside the die and therefore depends on the die length. $p_{entrance}$ and p_{exit} are the pressure losses due to the elongational flow at the entrance and the exit region (Bagley, 1957), respectively. Since the elongational properties can be related to the elasticity of the material, one way of evaluating the elastic effects is extrapolating the p_{die} values measured at varying die lengths L_d to L_d = 0 where $p_{viscous}$ theoretically becomes $p_{viscous}$ = 0 (Bagley, 1961). In this case, the Bagley pressure $p_{die} = p_{entrance} + p_{exit}$ characterizes the pressure loss due to elastic properties of the melt. For an