Carbohydrate Polymers 93 (2013) 492–498

Contents lists available at SciVerse ScienceDirect

Carbohydrate Polymers

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

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

Mario Horvat[a,*], M. Azad Emin[a], Bernhard Hochstein[b], Norbert Willenbacher[b], Heike Petra Schuchmann[a]

[a] Institute of Process Engineering in Life Sciences, Section I: Food Process Engineering, Karlsruhe Institute of Technology, Kaiserstraße 12, 76131 Karlsruhe, Germany
[b] Institute for Mechanical Process Engineering and Mechanics, Karlsruhe Institute of Technology, Kaiserstraße 12, 76131 Karlsruhe, Germany

ARTICLE INFO

Article history:
Received 20 August 2012
Received in revised form
10 December 2012
Accepted 13 December 2012
Available online 26 December 2012

Keywords:
Extrusion
Medium-chain triglycerides
Expansion
Bagley pressure
Elongational properties
Inline-rheometer

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

* Corresponding author. Tel.: +49 721 608 4 21 96; fax: +49 721 608 4 59 67.
E-mail address: mario.horvat@kit.edu (M. Horvat).

0144-8617/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.carbpol.2012.12.052

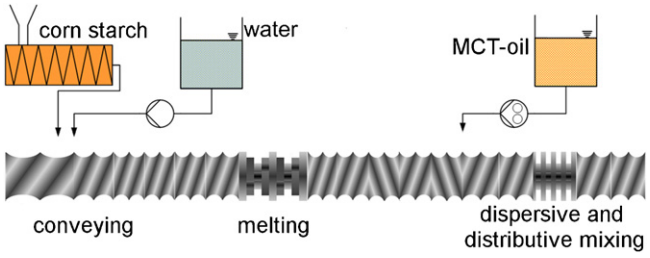

Fig. 1. Setup of the extruder, the screw geometry and feed locations of corn starch, water and MCT-oil.

(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.

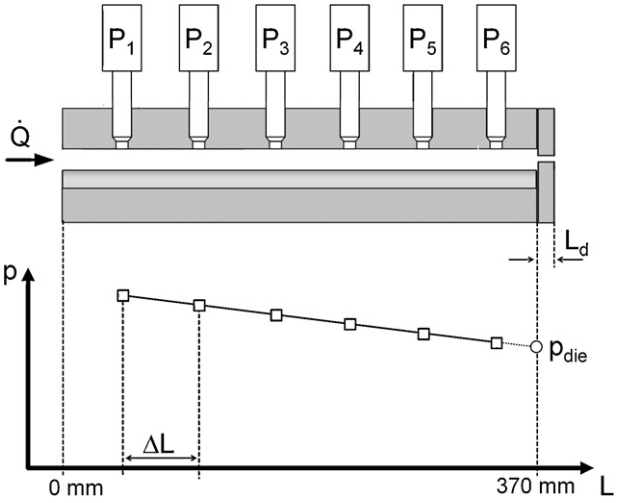

Fig. 2. Rheometer setup with pressure transducers and the corresponding measured pressure values along the slit channel. The total die pressure loss p_{die} is determined by linear extrapolation.

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

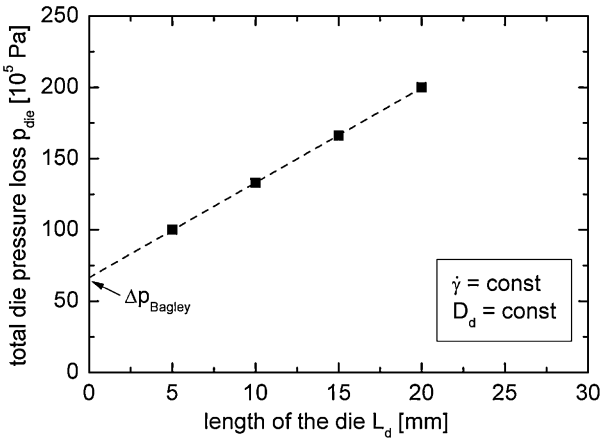

Fig. 3. Schematic Bagley plot of pressure values p_{die} determined by using different die lengths at constant shear rate and die diameter.

evaluation method of elastic properties according to Bagley correction, orifice dies with different lengths L_d of 10 mm, 15 mm and 25 mm were used. The obtained values of p_{die} were plotted against the die length L_d (see Fig. 3). In this Bagley plot, the elastic pressure loss was calculated from linear extrapolation to a theoretical die length L_d of 0.

2.2.3. Characterization of expansion

Longitudinal expansion index (*LEI*) was determined according to Eq. (4).

$$LEI = \frac{v_{ext}}{v_{die}} \tag{4}$$

The velocity of the extrudate after the orifice die v_{ext} was obtained by taking samples for a period of 5 s and subsequently measuring their lengths. The measurements were done in triplicates. The velocity in the die v_{die} was calculated with Eq. (5).

$$v_{die} = \frac{\dot{Q}_{melt}}{S_{die}} \tag{5}$$

S_{die} is the cross sectional area of the die (d_{die} = 3 mm). After cooling to room temperature, the diameter of the expanded samples d_{ext} was measured with a caliper. The average of 15 measurements was taken, from which the sectional expansion index (*SEI*) was calculated.

$$SEI = \left(\frac{d_{ext}}{d_{die}}\right)^2 \tag{6}$$

2.2.4. Water solubility index

The water solubility index (WSI) was determined using a modified method of Anderson, Conway, Pfeifer, and Griffin (1969). The samples were ground in a rotor beater mill (*Retsch SR 3*) at 50 Hz. Then the particles were fractionated by sieving at mesh sizes of 140 μm and 200 μm. The fraction obtained between the mesh sizes mentioned was used for further processing and dried overnight in an oven at 95 °C and used for further processing. 2.5 g of the sample were dispersed in 30 ml of deionized water, agitated at 30 °C for 30 min and centrifuged at 11,500 min^{-1} and 25 °C for 30 min. The supernatant was dried overnight at 95 °C. The weight of the dry supernatant was measured and the WSI was calculated according to Eq. (7). WSI analysis was performed in triplicate.

$$\text{WSI} = \frac{\text{Supernatant dry solidweight}}{\text{Sample dry weight}} \times 100\% \tag{7}$$

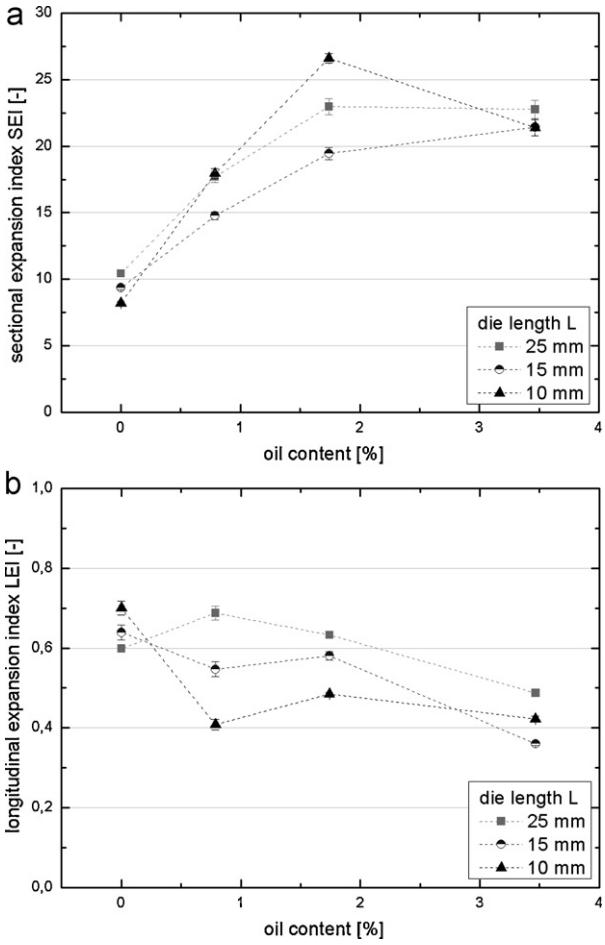

Fig. 4. (a) Sectional expansion index and (b) longitudinal expansion index as a function of oil content for three different die lengths.

2.2.5. Statistical analysis

The significance of the influence of oil content on SEI, LEI, shear viscosity, Bagley pressure and WSI was assessed using a one-way analysis of variance (ANOVA). A probability of $p < 0.05$ was assumed to characterize a significant result.

3. Results

3.1. Influence of oil content on expansion indices

Total bulk expansion is a result of radial and longitudinal expansion, which are evaluated by the sectional expansion index (SEI) and the longitudinal expansion index (LEI), respectively. In Fig. 4 these characteristic expansion indices are shown as a function of MCT-oil content for die lengths of L = 10 mm, 15 mm and 25 mm. In general, the SEI of oil loaded samples was up to about 3 times higher than of the samples without oil (Fig. 4a). Even at the lowest oil content of 0.8%, the SEI increased by about 50%. With a die length of 10 mm, the maximum SEI was observed at an oil content of 1.7%, whereas the samples extruded with 15 mm die length showed the maximum SEI at the oil content of 3.5%. On the other hand, a comparable enhancing effect of oil on the LEI was not observed (Fig. 4b). In contrast, the overall trend is a slight decrease in LEI with increasing oil content.

3.2. Influence of oil content on extrusion parameters and melt rheology

To find the key parameters changed by the addition of oil content and leading to the expansion behavior described above, the process

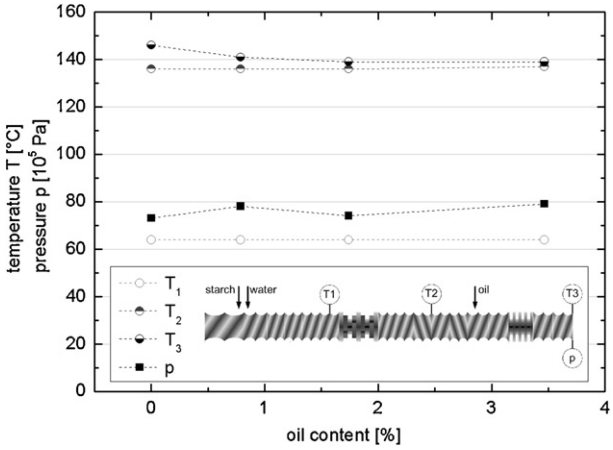

Fig. 5. Extrusion process parameters as a function of oil content. Temperatures T_1–T_3 measured at different sites along the extruder and pressure p before the exit.

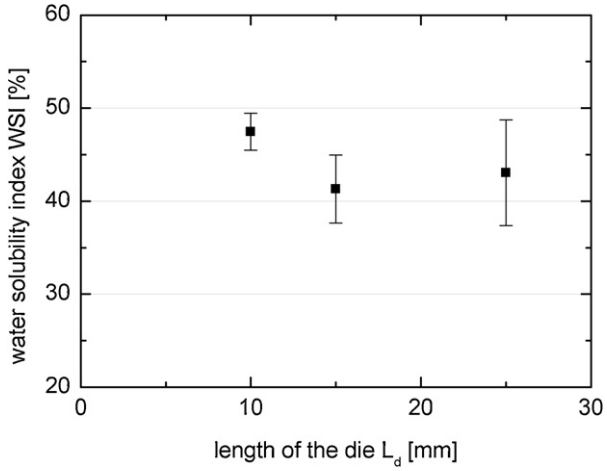

Fig. 7. Water solubility index of the samples without oil given as a function of the die length.

parameters were monitored during the experiments. Fig. 5 shows the melt temperature and pressure measured during the extrusion processing with the 25 mm die length as a function of oil content. Neither the temperatures of the melt measured at different sites along the extruder, nor the pressure at the die showed a remarkable change by the increase of oil content. Similar results were obtained with die lengths of 10 mm and 15 mm (results not shown).

It is known that the rheological properties of the matrix affect the expansion behavior (Street, 1968). We measured the shear viscosity of the starch melt during extrusion processing. Fig. 6 shows the apparent shear viscosity of the starch melt at a shear rate of $\dot{\gamma} = 9\,s^{-1}$ as a function of oil content. At all die lengths used the oil content had no significant influence on the apparent shear viscosity ($p > 0.05$). However, the results in Fig. 6 clearly show that increasing die length led to decrease in viscosity at the range of oil content studied.

To investigate the influence of the die length on starch degradation, the water solubility index (WSI) was measured. The WSI analysis was not applicable to the samples containing oil, since an undefined amount of oil was released during the milling and dispersing phase of the analysis. For this reason, only results of samples without oil are shown here. Nevertheless, the samples with oil are expected show similar results. Since oil was added after the highest shear section, it is assumed that oil had a negligible influence on further starch gelatinization and degradation (Liu, Halley, & Gilbert, 2010; van den Einde et al., 2004). Fig. 7 shows the WSI for the three

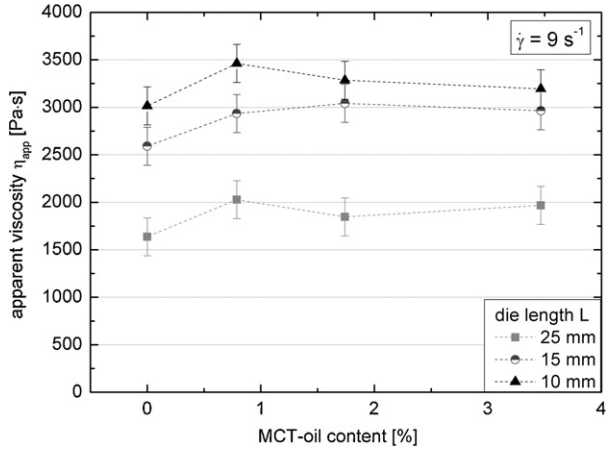

Fig. 6. Apparent shear viscosity at a constant shear rate as a function of oil content for three different die lengths.

die lengths used. The apparent decrease of WSI with increasing die length could not be proven to be significant ($p > 0.05$).

The Bagley method for determination of the die entrance pressure was used to estimate the elastic properties of the starch melt at various oil contents as described in Section 2.2.2. The total pressure loss is depicted in the Bagley plot as a function of L_d for varied oil content (Fig. 8). According to the Bagley method, the regression lines were extrapolated to $L_d = 0$. The results show that addition of 0.8% MCT-oil led to a significant increase of the resulting Bagley pressure from about 24.5 ± 0.5 bar to 35.7 ± 5.8 bar. At 1.7% and 3.5% oil content the Bagley pressure is 37.0 ± 2.1 bar and 35.1 ± 3.2 bar, respectively. This result suggests that oil increases the elastic properties of the starch melt already at very low content. Further increase in oil content, however, does not lead to further increase in the Bagley pressure.

4. Discussion

Incorporation of MCT-oil in molten starch via twin-screw extrusion processing led to an exceptional increase in sectional expansion up to 3 times (Fig. 4). In contrast, the longitudinal expansion was nearly unaffected by the oil content. The die length also had an influence on sectional expansion. Since the influence of the die length was comparably small and the overall trends were similar for all die lengths used, we restricted the discussion to the increase in expansion due to oil addition. In previous studies, the influence of oil on expansion was assumed to be a result of its lubricating effect leading to a change in starch conversion (Abu-hardan, Hill, & Farhat, 2011; Badrie & Mellowes, 1992). It must be noted that, in these studies, the oil was fed into the extruder together with starch and water. Due to higher lubrication, the starch molecules might be exposed to less mechanical stresses during extrusion processing. This effect can lead to a change in the viscosity, the pressure and the temperature of the melt in the extruder die (Della Valle, Buleon, Carreau, Lavoie, & Vergnes, 1998), which are the main parameters affecting the expansion (Mercier & Feillet, 1975). In contrast to the mentioned studies, we incorporated MCT-oil at the end of the extruder, where the starch plasticization, gelatinization and degradation were assumed to be already completed. This expectation is based on the findings of van den Einde et al. (2004) and Liu et al. (2010). They showed that the starch degradation is mainly driven by maximum shear stress applied. With the screw geometry and set-up chosen for this study, the maximum shear stresses were applied before the addition of oil (see Section 2.2.1). Our results in Fig. 5 support this hypothesis, since the process

parameters temperature, pressure and shear viscosity showed no significant change at the range of oil content investigated. It can be assumed that the material properties inside the extruder and, thus, thermomechanical history of the starch are not affected by the oil. Hence, other parameters or material properties are expected to be the reason of tripled sectional expansion by the addition of oil.

In the following section the possible influence of the incorporated oil on each mechanism of expansion will be discussed. Moraru and Kokini (2003) reported that the expansion of extruded starch melts at the die exit consists of only few major steps: (a) bubble nucleation, (b) extrudate swell with significant bubble growth and, finally, (c) bubble collapse until the matrix becomes glassy and solid.

4.1. Nucleation

In order to relate the findings of the rheological behavior to nucleation, the LEI and the SEI have to be reconsidered separately. We showed that LEI is only slightly influenced by the addition of oil (Fig. 4b). Longitudinal expansion is expected to be strongly influenced by the nucleation and more related to viscous properties of the matrix (Alvarez-Martinez et al., 1988). When bubbles begin to nucleate inside the die, the bubble growth is restricted by the capillary walls leading to favored longitudinal expansion. The nucleation starts at the time when the pressure falls below vapor pressure of the fluid. The nucleation is therefore influenced by the pressure profile in the extruder die, which is a function of shear viscosity. Addition of oil in the formulation can lead to a lower glass transition temperature as Madrigal, Sandoval, and Müller (2011) showed for corn oil in cassava starch. A decrease in glass transition temperature reduces the viscosity of the melt (Fan, Mitchell, & Blanshard, 1996). Such a change in the viscosity with increasing oil content was not observed in our study (Fig. 6). In addition, we observed that just a few bubbles or even a single bubble were driving the expansion of the extrudates at the die exit (images not shown). Increased nucleation would lead to a more homogeneous pore structure, higher cell density and lower wall thickness (Zhai, Park, & Kontopoulou, 2011). Zhai et al. (2011) also found that with increased nucleation SEI even decreased. These results clarify that an increased nucleation unlikely is the reason for the strong increase in sectional expansion.

4.2. Bubble growth

Apart from nucleation, bubble growth is the second important step in the expansion process and it is supposed to be governed by the rheological (viscous as well as elastic) properties of the matrix. Bubble growth after the die exit mainly affects the sectional expansion. Despite the unmodified apparent shear viscosity mentioned before, the SEI increased upon oil addition (Fig. 4a). Therefore, the elastic behavior possibly is the reason of the 3-fold increase in sectional expansion with the addition of oil. In contrast to longitudinal expansion, the sectional expansion can only start after the matrix leaves the die. After leaving the die, the matrix is mainly exposed to biaxial extension due to bubble growth. It is most likely that the sectional expansion is more affected from extensional properties than the longitudinal expansion (Launay & Lisch, 1983).

To perform a reliable Bagley analysis, a possible influence of die length on starch degradation must be excluded. The results of WSI, which is correlated to molecular breakdown, show that there is no notable change in water solubility at different die lengths (Fig. 7). Moreover, Fig. 8 depicts that there is an almost linear increase in die pressure p_{die} with increasing orifice die length, as proposed by Bagley (1961). These results support the assumption that the starch structure remains unmodified with increasing die length, showing the applicability of the Bagley plot for extruded corn starch.

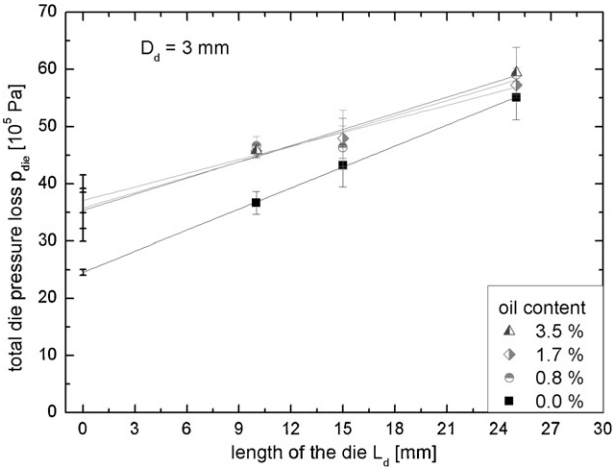

Fig. 8. Extrapolated pressure loss at the entrance of the die as a function of the die length (Bagley plot).

Fig. 8 illustrates that the extrapolated Bagley pressure remarkably increases by about 44% upon addition of oil, indicating a change in elongational properties of the melt. It is well-known that a dispersed phase can have an effect on the bulk elasticity or elongational viscosity. For instance, some researchers observed elasticity improvement of highly concentrated oil-in-water emulsions at dispersed phase contents of 70% (Derkach, 2009; Masalova & Malkin, 2007). In the case of polymers, mostly the influence of solid nano-particle fillers on the mechanical properties of the matrix was investigated. Due to challenges in the measurement of rheological properties of starch melts, there is no publication showing the influence of low amounts of oil on the elongational viscosity or the elasticity. At the low oil contents used in this work, molecular or micro-structural interactions between starch and oil, such as amylose-lipid complexes or capillary suspensions, may be the reason for a change in the elasticity (Koos & Willenbacher, 2011; Mercier, Charbonniere, Grebaut, & Gueriviere, 1980). Though, amylose-lipid complexation is not expected in the system used in our study. Mercier et al. (1980) reported that triglycerides, such as MCT-oil, are too large for a successful complex formation. Nonetheless, our results show that upon addition of MCT-oil the Bagley pressure increases significantly while the shear viscosity is less influenced (Figs. 6 and 8).

It was shown for several polymers that bubble growth in foaming processes depends on the elongational behavior of the melt (Ruinaard, 2006; Stange & Munstedt, 2006). Furthermore, it is known, that another elastic property, namely the first normal stress difference N_1, is responsible for die swell, which might also contribute to sectional expansion in this case (Faller, Huff, & Hsieh, 1995). The elongational viscosity as well as the first normal stress difference are related to the Bagley pressure (Cogswell, 1972; Gleissle, 1988). Our results suggest that the favored sectional expansion by the addition of oil might result from the change in the elastic properties. It must be mentioned that the measured Bagley pressure was unaffected by the increase in oil content from 0.8% up to 3.5%, although the sectional expansion continued to increase. Hence, strong conclusion is still challenging to draw, due to the complex multivariate thermomechanical mechanism behind the water-vapor induced expansion.

Since temperature and the corresponding vapor pressure are further key parameters of the bubble growth, the influence of oil addition on the thermal energy and amount of evaporated water must be considered. Total heat capacity of oil is in the same range as pure water–starch mixtures (about $2\,J\,g^{-1}\,K^{-1}$) according to DSC measurements performed by Morad, Idrees, and Hasan (1995)

and Noel and Ring (1992). In addition, slight enthalpy changes on account of oil heat capacity with an oil content of up to 3.5% are very low compared to water enthalpy of vaporization. Nevertheless, the influence of changed thermal properties must be further investigated.

4.3. Shrinkage and matrix solidification

During cooling of the extrudate leaving the die, the matrix finally becomes solid. The phase transition from rubbery into glassy state is responsible for matrix solidification (Della Valle et al., 1997; Fan et al., 1996). While approaching glass transition temperature the viscosity increases dramatically, leading to solidification of the melt (White & Cakebread, 1966). Although we measured no effect on the shear viscosity, a slight change in glass transition temperature due to oil could have an impact on the solidification temperature of the melt, resulting in a different amount of shrinkage. Since shrinkage was not observed in all the samples, a change in glass transition is not expected to be the reason for the enhanced expansion.

5. Conclusions

Water-vapor induced expansion of an extruded starch based melt was enhanced by up to 3 times by the addition of medium-chain triglycerides. Addition of MCT-oil in the range of 0.8–3.5% was sufficient to observe this phenomenon. In particular, the sectional expansion index increased whereas the longitudinal expansion index slightly decreased due to the addition of oil. The reason of the remarkable increase in sectional expansion was investigated by analyzing the process parameters. The results showed that torque, temperature and pressure in the extruder remained unaffected by addition of the oil. Furthermore, oil showed no significant influence on the shear viscosity of the starch matrix. In contrast, the Bagley pressure increased significantly upon oil addition, suggesting a change in elongational properties. This change in elongational behavior is expected to play an important role in the increased sectional expansion. Further investigation of the elongational behavior of starch melts, using the set up introduced in our study, would aid to gain deeper insights into the mechanisms of increased expansion due to addition of oil.

Acknowledgments

We would like to thank Dilay Aktürk, Andrea Butterbrodt and Kerstin Sauther for the experimental work.

References

Abu-hardan, M., Hill, S. E., & Farhat, I. (2011). Starch conversion and expansion behaviour of wheat starch cooked with either; palm soybean or sunflower oils in a co-rotating intermeshing twin-screw extruder. *International Journal of Food Science and Technology*, *46*, 268–274.

Alvarez-Martinez, L., Kondury, K. P., & Harper, J. M. (1988). A general-model for expansion of extruded products. *Journal of Food Science*, *53*, 609–615.

Anderson, R. A., Conway, H. F., Pfeifer, V. F., & Griffin, E. L. (1969). Gelatinization of corn grits by roll and extrusion cooking. *Cereal Science Today*, *14*, 4–11.

Badrie, N., & Mellowes, W. A. (1992). Soybean flour oil and wheat bran effects on characteristics of cassava (Manihot-Esculenta Crantz) flour extrudate. *Journal of Food Science*, *57*, 108–111.

Bagley, E. B. (1957). End corrections in the capillary flow of polyethylene. *Journal of Applied Physics*, *5*, 624–627.

Bagley, E. B. (1961). The separation of elastic and viscous effects in polymer flow. *Transactions of the Society of Rheology*, *5*, 355–368.

Baird, D. G. (2008). First normal stress difference measurements for polymer melts at high shear rates in a slit-die using hole and exit pressure data. *Journal of Non-Newtonian Fluid Mechanics*, *148*, 13–23.

Bhattacharya, M., & Padmanabhan, M. (1994). Evaluation of the hole pressure method to measure the 1st normal stress difference of corn meal dough during extrusion-cooking. *Journal of Texture Studies*, *25*, 241–265.

Cogswell, F. N. (1972). Measuring extensional rheology of polymer melts. *Transactions of the Society of Rheology*, *16*, 383–403.

Della Valle, G., Vergnes, B., Colonna, P., & Patria, A. (1997). Relations between rheological properties of molten starches and their expansion behaviour in extrusion. *Journal of Food Engineering*, *31*, 277–296.

Della Valle, G., Buleon, A., Carreau, P. J., Lavoie, P. A., & Vergnes, B. (1998). Relationship between structure and viscoelastic behavior of plasticized starch. *Journal of Rheology*, *42*, 507–525.

Derkach, S. R. (2009). Rheology of emulsions. *Advances in Colloid and Interface Science*, *151*, 1–23.

Faller, J. F., Huff, H. E., & Hsieh, F. (1995). Evaluation of die swell and volumetric expansion in corn meal extrudates. *Journal of Food Process Engineering*, *18*, 287–306.

Fan, J. T., Mitchell, J. R., & Blanshard, J. M. V. (1996). The effect of sugars on the extrusion of maize grits. 1. The role of the glass transition in determining product density and shape. *International Journal of Food Science and Technology*, *31*, 55–65.

Faubion, J. M., & Hoseney, R. C. (1982). High-temperature short-time extrusion cooking of wheat-starch and flour. 2. Effect of protein and lipid on extrudate properties. *Cereal Chemistry*, *59*, 533–537.

Gleissle, W. (1988). First normal stress difference and Bagley-correction. In *Proceedings of the Xth international congress of rheology* (pp. 350–352).

Horn, D. (1989). Preparation and characterization of microdisperse bioavailable carotenoid hydrosols. *Angewandte Makromolekulare Chemie*, *166*, 139–153.

Kokini, J. L., Chang, C. N., & Lai, L. S. (1992). The role of rheological properties on extrudate expansion. In J. L. Kokini, C. T. Ho, & M. V. Karwe (Eds.), *Food extrusion science and technology* (pp. 631–653). New York: Marcel Dekker.

Koos, E., & Willenbacher, N. (2011). Capillary forces in suspension rheology. *Science*, *331*, 897–900.

Launay, B., & Lisch, J. M. (1983). Twin-screw extrusion cooking of starches: Flow behaviour of starch pastes expansion and mechanical properties of extrudates. *Journal of Food Engineering*, *2*, 259–280.

Lin, S., Hsieh, F., & Huff, H. E. (1997). Effects of lipids and processing conditions on degree of starch gelatinization of extruded dry pet food. *Food Science and Technology-Lebensmittel-Wissenschaft & Technologie*, *30*, 754–761.

Liu, W. C., Halley, P. J., & Gilbert, R. G. (2010). Mechanism of degradation of starch, a highly branched polymer during extrusion. *Macromolecules*, *43*, 2855–2864.

Madrigal, L., Sandoval, A. J., & Müller, A. J. (2011). Effects of corn oil on glass transition temperatures of cassava starch. *Carbohydrate Polymers*, *85*, 875–884.

Masalova, I., & Malkin, A. (2007). Rheology of highly concentrated emulsions – Concentration and droplet size dependencies. *Applied Rheology*, *17*, 1–9.

Mercier, C., & Feillet, P. (1975). Modification of carbohydrate components by extrusion-cooking of cereal products. *Cereal Chemistry*, *52*, 283–297.

Mercier, C., Charbonniere, R., Grebaut, J., & Gueriviere, J. F. D. L. (1980). Formation of amylose-lipid complexes by twin-screw extrusion cooking of manioc starch. *Cereal Chemistry*, *57*(1), 4–9.

Micic, P., Bhattacharya, S. N., & Field, G. (1998). Transient elongational viscosity of LLDPE/LDPE blends and its relevance to bubble stability in the film blowing process. *Polymer Engineering and Science*, *38*, 1685–1693.

Morad, N. A., Idrees, M., & Hasan, A. A. (1995). Specific heat capacities of pure triglycerides by heat-flux differential scanning calorimetry. *Journal of Thermal Analysis*, *45*, 1449–1461.

Moraru, C. I., & Kokini, J. L. (2003). Nucleation and expansion during extrusion and microwave heating of cereal foods. *Comprehensive Reviews in Food Science and Food Safety*, *2*, 120–138.

Munstedt, H., Kurzbeck, S., & Kaschta, J. (1996). Elongational properties of polyolefin melts. In *Proceedings XIIth international congress on rheology* , p. 89.

Noel, R. T., & Ring, S. G. (1992). A study of the heat capacity of starch/water mixtures. *Carbohydrate Research*, *227*, 203–213.

Padmanabhan, M., & Bhattacharya, M. (1991). Flow behavior and exit pressures of corn meal under high-shear-high-temperature extrusion conditions using a slit die. *Journal of Rheology*, *35*, 315–343.

Pai, D. A., Blake, O. A., Hamaker, B. R., & Campanella, O. H. (2009). Importance of extensional rheological properties on fiber-enriched corn extrudates. *Journal of Cereal Science*, *50*, 227–234.

Ribeiro, H. S., Guerrero, J. M. M., Briviba, K., Rechkemmer, G., Schuchmann, H. P., & Schubert, H. (2006). Cellular uptake of carotenoid-loaded oil-in-water emulsions in colon carcinoma cells in vitro. *Journal of Agricultural and Food Chemistry*, *54*, 9366–9369.

Ribeiro, H. S., Schuchmann, H. P., Engel, R., Briviba, K., & Walz, E. (2009). Encapsulation of carotenoids and vitamins. In N. J. Zuidam, & V. A. Nedovic (Eds.), *Encapsulation technologies for food active ingredients and food processing*. Heidelberg: Springer.

Ruinaard, H. (2006). Elongational viscosity as a tool to predict the foamability of polyolefins. *Journal of Cellular Plastics*, *42*, 207–220.

Singh, N., & Smith, A. C. (1997). A comparison of wheat starch whole wheat meal and oat flour in the extrusion cooking process. *Journal of Food Engineering*, *34*, 15–32.

Stange, J., & Munstedt, H. (2006). Rheological properties and foaming behavior of polypropylenes with different molecular structures. *Journal of Rheology*, *50*, 907–923.

Street, J. R. (1968). The rheology of phase growth in elastic liquids. *Transactions of the Society of Rheology*, *12*, 103.

van den Einde, R. M., Bolsius, A., van Soest, J. J. G., Janssen, L. P. B. M., van der Goot, A. J., & Boom, R. M. (2004). The effect of thermomechanical treatment on starch breakdown and the consequences for process design. *Carbohydrate Polymers*, *55*, 57–63.

Vergnes, B., Della Valle, G., & Tayeb, J. (1993). A specific slit die Rheometer for extruded starchy products. Design validation and application to maize starch. *Rheologica Acta*, *32*, 465–476.

White, G. W., & Cakebread, S. H. (1966). The glassy state in certain sugar-containing food products. *International Journal of Food Science & Technology*, *1*, 73–82.

Zhai, W. T., Park, C. B., & Kontopoulou, M. (2011). Nanosilica addition dramatically improves the cell morphology and expansion ratio of polypropylene heterophasic copolymer foams blown in continuous extrusion. *Industrial & Engineering Chemistry Research*, *50*, 7282–7289.