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Measurement of the true melt temperature in a twin-screw extrusion processing of starch based matrices via infrared sensor

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ABSTRACT

True temperature distribution in extruded melts is a crucial information for food extrusion applications, in which the material transformations and reactions can otherwise not be fully controlled. Conventional measurements by thermocouple are known to be critical as response time is long and measured data are influenced by surrounding. Infrared sensors offer the advantage of quick response time in the form of a non-invasive probe to measure the temperature distribution. However, infrared sensors need to be calibrated on the material to be investigated. For this purpose, an inline calibration method was developed and verified. The results show that neither the extrusion conditions at the range investigated nor the matrix type (i.e. starch or wheat flour) have a significant influence on the surface and volumetric emissivity of biopolymeric melt. Furthermore, the infrared sensor was verified in a twin screw extruder and the results are compared to the measurements by a conventional thermocouple. The infrared sensor was able to capture the temperature variations generated by rotation of screws.

1. Introduction

Extrusion is one of the few processes in the food industry which has been continuously developed since its invention (Bouvier and Campanella, 2014; Maskan and Altan, 2011). One of the common application areas is cereal-processing, in which extrusion technology is used for converting cereal flours by kneading, cooking/plasticizing, forming, and structuring to produce pasta, ready-to-eat (RTE) food products and functional ingredients. Another unique application area is protein processing, in which plant or diary based proteins are cooked/textured and then structured to produce meat analogs or substitutes. Extrusion has been also used in many other areas, including confectionaries, pet foods, and even extraction/separation applications (Bouvier and Campanella, 2014).

Regardless of its various application areas, the control and development of extrusion processes have always been very challenging. Extrusion is a thermomechanical process, in which materials are physically and chemically transformed due to thermal and mechanical stresses generated by the screws rotating and the barrels heated. However, measurement of thermomechanical stresses within an extruder is not a trivial task leaving the extrusion to be a black box.

Although the influence of mechanical stresses (i.e. shear and elongational stresses) on material transformations is not yet well understood, the control of thermal stress profile during extrusion processing is essential to control the resulting product characteristics (Emin et al., 2012; Hirth et al., 2015; Riaz et al., 2009). The temperature of extruded material plays an important role at every stage of extrusion processing, from physicochemical changes in the extruder to the product structuring at the die exit, because the structural transformations (e.g. glass transition, melting, fragmentation, reaction rates) as well as key material properties (e.g. viscosity, vapor pressure) depends on the temperature (Horvat et al., 2013a, 2013b; Van den Einde et al., 2003). Temperature control becomes even more important at the design of complex food products, such as functional foods in which the functional ingredients are often very susceptible to high thermal stresses (Camire et al., 1990; Hirth et al., 2014). Therefore, high accuracy melt temperature measurements are required to achieve good control of the extrusion process and the resulting product characteristics.

Temperature measurements during extrusion processing are usually made using thermocouples that are inserted in

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instrumentation ports along the extruder barrel and die head (Bouvier and Campanella, 2014; Rauwendaal, 2014). The thermocouple junction is embedded within a metal probe to protect it from the intense extrusion conditions (i.e. high pressure and shear). Thermocouple probes are conventionally flush-mounted to measure the melt temperature without disrupting the melt flow. However, previous studies (Davis, 1988; Karwe and Godavarti, 1997; Maier, 1996) showed that such measurements are highly susceptible to the heat conduction from the barrel wall to the thermocouple junction, and therefore the measured temperature is negatively affected, and often does not represent the true melt temperature. These measurements can be improved to a certain extent by intruding the thermocouple probe into melt (Karwe and Godavarti, 1997; Maier, 1996). However, in most extruders, there is not enough space between the complex geometry of rotating screws and barrel wall for an intruding thermocouple measuring the temperature accurately. Intruding probes also disrupt the melt flow in that area which is especially critical at the die exit. Furthermore, thermocouples have relatively slow response time which may vary from 1 to several seconds allowing only measuring time weighted average temperatures (Karwe and Godavarti, 1997; Rauwendaal, 2014). On the other hand, the viscous dissipation generated by the rotating screws leads to a temperature distribution, and local temperature maxima (Emin and Schuchmann, 2013; Ishikawa et al., 2001; Kohlgrüber, 2007). This is especially of special interest in food extrusion, which however cannot be monitored by thermocouples.

Similar issues have been known in the field of polymer extrusion since over two decades, and therefore, many studies had been focused on development of quick and non-invasive techniques to monitor the true melt temperature within the extruder and the die exit. These techniques include infrared (Barron, 1994; Chen, 1992; Davis, 1988; Karwe and Godavarti, 1997; Maier, 1996; Obendrauf et al., 1998), ultrasound (Chen et al., 1999), fluorescence spectroscopy (Bur et al., 2003), and tomography measurements (Frisullo et al., 2009; Yang et al., 2008). In infrared measurements, the radiation energy emitted by the melt is used to monitor the temperature of material. The ultrasonic technique is based on measuring the ultrasonic velocity in a hot melt which is then transformed to temperature by means of a precisely measured velocity–temperature relation. In fluorescence spectroscopy technique, a small amount of temperature sensitive dye is added into extruded material and the local temperature is measured by monitoring spectral response of the dye. The tomography is based on measuring the capacitance from a multi-electrode sensor surrounding an industrial process containing different permittivity, which is a function of temperature.

From these techniques, infrared measurements have already been proven to be an accurate and sensitive method to monitor the temperature of extruded melts (Chen, 1992; Karwe and Godavarti, 1997; Maier, 1996), and are therefore the focus of this study. Infrared sensors offer the advantage of quick response time in the form of a non-invasive probe to measure the temperature distribution of extruded biopolymers. Furthermore, in contrary to thermocouples, there are no errors due to heat conduction (Karwe and Godavarti, 1997; Maier, 1996). Infrared measurements are based on the thermal radiation emitted by the material of temperature T [K] that follows Planck's law, i.e. radiation power at the wavelength λ [μm] is

$$E\,(\lambda,T)=\varepsilon\frac{C_1}{\lambda^5}\frac{1}{\exp\frac{C_2}{\lambda T}-1}\;\left[\mathrm{W}\big/\mathrm{m}^2\mu\mathrm{m}\right] \tag{1}$$

per unit area and unit wavelength, where $C_1 = 3.74 \times 10^8$ Wμm^4/m^2 and $C_2 = 1.44 \times 10^4$ μmK. ε is the emissivity that varies between 0 and 1 depending on the material and the surface condition of the object. The object that emits thermal radiation most efficiently ($\varepsilon = 1$) is called a blackbody. The total power P of the emission increases notably with temperature T:

$$P(T)=\int_{\lambda_1}^{\lambda_2}E(\lambda)d\lambda\quad\left[\mathrm{W}\big/\mathrm{m}^2\right] \tag{2}$$

where λ_1 and λ_2 show the lower and upper limit of the spectral range measured, respectively. The spectral range is defined by the spectral performance of the optical components: a photosensor, a focusing lens, and an optical fiber (Lai and Rietveld, 1996; Maier, 1996). One can, therefore, determine the temperature T of the object from the measured radiation power P by using the calibration curve of P vs. T, which are taken prior to the measurement by recording the signal for a material of known temperature.

Such measurements are straightforward, if the radiation is mainly emitted from the surface of the material (i.e. opaque material), which is the case for most foods. On the other hand, interpretation of the infrared radiation emitted from a biopolymeric melt flow can be more complicated, as the emitted radiation originates from the melt surface and its subsurface, sometimes even including the metal surfaces under the measured volume (Lai and Rietveld, 1996; Maier, 1996). For this reason, the IR sensor yield weighted values of the temperature of a defined measuring volume (Maier, 1996). Therefore, additional to the surface emissivity, the volumetric emissivity of the material must be considered during the calibration of infrared sensors for different applications, as it also depends on the material characteristics (Maier, 1996). This might be especially important for food extrusion, as the material characteristics depend on the extruded formulation, which can highly vary in protein, polysaccharide, fat or water content. Furthermore, the extent of the thermomechanical treatment in extrusion affects the material characteristics (e.g. molecular size distribution, crystallinity of starch) as well (Brümmer et al., 2002; Van Den Einde et al., 2004).

Despite the potential of infrared sensors, their application in food extrusion to measure the detailed temperature distribution has only addressed by a limited number of publications (i.e. Karwe and Godavarti, 1997). Karwe and Godavarti performed their study on corn flour and high amylose maize starch (i.e. Hylon 7) by using a twin screw extruder. They clearly showed that there are substantial differences between time averaged temperature measurements by IR sensors and flush mounted thermocouples, and these differences depend on the processing conditions. In this study of Karwe and Godavarti, the sensors are mounted at the very last part of screws, at which specific spacers (i.e. no screw elements) are used, allowing them to compare infrared sensors to protruded thermocouples. Furthermore, the emissivity of extruded materials is assumed to be constant and equal the emissivity of bread dough. One of the main challenges concerning a calibration of infrared sensors on biopolymeric melts (e.g. starch or proteins) is the necessity of elevated temperatures and pressures to melt the biopolymer, and to prevent the evaporation of water. Furthermore, in extrusion, biopolymers are often melted at low water contents (e.g. about 20% for breakfast cereals) requiring additional mechanical treatment. Under these experimental circumstances, any offline calibration systems are hardly applicable.

This study aims at the development of a method for the calibration of an infrared sensor for extruded biopolymeric melts and testing this sensor in extrusion processing of starch based matrices as a model biopolymeric material.