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Simulation of the convective drying process with automatic control of surface temperature

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ABSTRACT

In convective drying of fruits and vegetables the maximum temperature develops at the product surface. Furthermore, heat sensitive products can be subjected to high air temperatures in the first stage of drying where the difference between air temperature and wet bulb temperature of the product is still very high. Automatic control of the surface temperature, avoiding exceeding of the maximum allowable temperature, can guarantee for the best drying results in terms of product quality.

In the study presented, a lumped parameter model, based on experimental results, for both the drying process of apple slices as well as the automatic control functionality is proposed. The simulation model shows close correlation with experimental data and can be used to determine optimum control and process parameters for convective drying of apples slices. Application of this strategy leads to a significant decrease of drying time and, potentially, increase of process efficiency and product quality.

1. Introduction

Preservation of sensitive agricultural products using convection drying is commonly used. It is well known that most biological foodstuffs are sensitive to high temperatures and long drying times leading to structural, organoleptic and nutritional changes. Although in recent years there has been an increasing demand for high quality dried products that retain their natural appearance (Fernandes et al., 2011; Krokida et al., 1998; Kiranoudis and Markatos, 2000; Nijhuis et al., 1998), the influence of drying conditions on product quality is still not fully known (Lewicki, 2006). Furthermore, many settings for industrial drying processes had been found experimentally years or even decades ago and their validity has not yet been evaluated (Mujumdar, 2007). This leads to a great need for optimization of the actual process settings, focussing on product quality criteria.

Jumah et al. (2007) stated that dryer automation could improve efficiency and help to meet consumer needs regarding product quality. Chou and Chua (2003) investigated the influence of different air temperature profiles on product quality and found that colour changes, as well as vitamin C content of heat sensitive biological materials, could be minimized when a stepwise variation of the air temperature with high initial temperature was applied. Ho et al. (2002) observed a positive influence on product quality when drying conditions were changed periodically. Furthermore, it could be proven that even heat sensitive biological products can be exposed to high air temperatures during the first stage of drying without being damaged (Chua et al., 2000; Sturm, 2010).

Sturm et al. (2009, 2012) developed a laboratory dryer that allowed for continuous non-invasive measurement of product temperature and automatic control thereof. Sturm et al. (2010, 2014) established a surface temperature control strategy that showed advantages regarding product quality in terms of colour, shrinkage and rehydration characteristics when compared to air temperature control.

The fundamental mechanisms of heat and mass transfer have been known for a long time (Krischer and Kast, 1978). According to Mujumdar (2007), transport of moisture can take one or several of the following forms: diffusion of the liquid phase (if the product temperature is lower than the evaporation temperature of the liquid), steam diffusion (when the liquid evaporates within the product), Knutsen's diffusion (very low temperatures and pressures), hygrostatic pressure difference (when the inner evaporation rate is higher than the steam transport rate through the solid to the particle surface), combinations of the mechanisms described.

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However, due to the coupled heat and mass transport, the changing product characteristics and shrinkage, the drying process is very complex. Therefore, the related equations can only be solved numerically (Hernandez et al., 2000; Białobrzewski, 2006).

Application of simulation methods is an efficient and powerful tool for evaluation and display of thermal processes in the food industry (Wang and Sun, 2003). In the past, these mechanisms were described with models of varying complexity. The simplest models only account for the mass transfer, assuming the drying process evolves under quasi isothermal conditions (Akpinar et al., 2003). The second degree of detail includes the heat and mass transfer under consideration of the temperature dependent diffusion coefficient. The use of empirical and semi-empirical models is very popular in this context. Several authors have applied these approaches for the simulation of apples (Doymaz, 2009; Kaya et al., 2007; Menges und Ertekin, 2006; Sacilik und Elicin, 2006; Seiiedlou et al., 2010; Vega-Gálvez et al., 2008; Wang et al., 2007; Zarein et al., 2013).

However, such drying models are only valid for the processing conditions and product characteristics they were developed for (Seiiedlou et al., 2010). In model development, assumptions such as simplified geometry, constant thermo-physical characteristics, constant heat and mass transfer and neglect of changes in volume throughout the process are prevalent (Wang und Sun, 2003). Whilst these assumptions simplify the model they lead to a reduced capability of the model to depict the experimental data of the drying kinetics (Hernandez et al., 2000).

In the area of the simulation of drying of apples, the most commonly used assumption is the neglect of the shrinkage throughout the process (Esfahani et al., 2014; Jun et al., 1998; Kaya et al., 2007; Lamnatou et al., 2010; Oztop und Akpinar, 2008; Wang et al., 2011). Often there also is no differentiation between mass transport in the liquid and gaseous phase (Białobrzewski, 2006; Esfahani et al., 2014; Golestani et al., 2013; Jun et al., 1998), or the thermo-physical characteristics are assumed to be constant (Esfahani et al., 2014; Golestani et al., 2013; Oztop und Akpinar, 2008).

However, several authors showed that the shrinkage significantly impacts on the validity of simulation models. Białobrzewski (2006) found that changed heat and mass transfer which result from shrinkage, directly influence product temperature as well as moisture content. Golestani et al. (2013) modelled the drying process of apples with and without consideration of shrinkage. They found that this significantly changed the effective diffusivity and influenced the temperature- and moisture distribution within the product.

Mayor and Sereno (2004) claimed that shrinkage influenced the quality of the product and therefore needs to be accounted for when temperature and moisture profiles within a product are predicted. Curcio und Aversa (2014) also found a significance of changes in shape within the drying material on transport phenomena during drying. Chen (2007) stated, that solely accounting for the diffusion within the liquid phase leads to unsteady results.

To better understand transport phenomena, multi-phase models, reflecting local water distribution in the liquid, as well as the gaseous phase, need to be applied (Putranto and Chen, 2013). Baini und Langrish's (2007) work showed that Fick's diffusion model was suited to simulate instationary drying if the changes in product temperature and humidity within the product are accounted for.

A multitude of publications on simulation of apple drying can be found (Chiang and Petersen, 1987; Vergara et al., 1997; Jun et al., 1998; Krokida et al., 2000; Lewicki and Łukaszuk, 2000; Moreira et al., 2000; Białobrzewski, 2006; Bravo et al., 2009; Doymaz, 2009; Lin et al., 2009; Putranto et al., 2011) but there has been no work focussing on the simulation of a constant surface temperature controlled drying process for apple slices.

In the work presented, a lumped parameter model of the drying material with implemented automatic process control was established using discretization and calculation methods known from aerospace engineering. Information about the implementation of automatic control features in ESATAN Models was given by Hofacker et al. (1991). The aim of this study was to develop a model that allows in-depth analysis of temperature, water and vapor content, shrinkage and other quality changes during surface temperature controlled drying of apples.

2. Materials and methods

A lumped parameter model established by Hugenschmidt and Hofacker for the simulation of constant air temperature drying of apples and specified in (Hugenschmidt and Hofacker, 2011a) and (Hugenschmidt and Hofacker, 2011b) was extended for surface temperature control as described below. The control parameters were fitted to experimental data. The simulation results obtained for several air and dew point temperatures as well as different air velocities then were compared to experimental data.

2.1. Experimental materials and methods

Apples of the Jonagold variety were sourced from a farmer in the Lake Constance region (Germany) and stored at 4 °C after purchase. Raw material was cut into slices of 3.9 mm + −0.2 mm thickness with an inner and outer diameter of 20 mm and 72 mm respectively. Ripeness was determined by the evaluation of the ratio between green and yellow of the fruit skin.

Drying tests were carried out using a precision dryer developed by Sturm (2010) which is described in detail by Sturm et al. (2012). The overflow mode was used and the product temperature controlled method described by Sturm et al. (2014) was applied.

For the testing the dryer was not pre-heated but started when the product was placed in the drying chamber. Apple slices were distributed as described by Sturm et al. (2012). Seven slices from a single apple were used for each test with a total resulting weight of approximately 90 g. Tests were conducted at 35, 40, 47.5, 55 and 60 °C maximum product temperature. Maximum air temperature was limited to 100 °C to simulate the maximum temperature that can be reached by the industrial drying system for which the strategy was developed. Dew point temperature was set to 5.0, 10.0, 17.5,25 and 30 °C with air velocities of 2.0, 2.6, 3.4, 4.2 and 4.8 m/s. The drying process was determined at a moisture content of approximately 0.13 g_W/g_{DM} which is typically used for dried apple products (desorption $a_W = 0.5$ (Wolf et al. (1972); adsorption $a_W = 0.52 \ldots 0.54$ (Wolf et al., 1972; Lewicki and Lenart, 1977). During drying product temperature, air temperature and weight were measured continuously.

2.2. Mathematical model

Coupled partial differential equations describing simultaneous heat and mass transport within the drying material were solved by discretizing apple slices in nodes, representing the finite elements of the problem area (Fig. 1). Nodes of height *s* and exchange area *A* were treated as isothermal and as of uniform moisture content. The governing partial differential equations were transformed into a system of non-linear equations solved by using an implicit forward backward differencing method.

Heat flow and mass streams in liquid and gaseous state ($\dot{H}_J, \dot{M}_{wj}, \dot{M}_{vj}$) between node *j* and *j+1* were calculated by analogue mathematical approaches.