Journal of Food Engineering 242 (2019) 68–75

Contents lists available at ScienceDirect

Journal of Food Engineering

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

Conductive thin film drying kinetics relevant to drum drying

Jun Qiu, Koen Kloosterboer, Yang Guo, Remko M. Boom, Maarten A.I. Schutyser*

Laboratory of Food Process Engineering, Wageningen University, Bornse Weilanden 9, 6708WG Wageningen, P.O. Box 17, 6700, AA Wageningen, the Netherlands

ARTICLE INFO

Keywords:
Conductive drying
Thin film
Drying kinetics
Boiling behavior
Vapor formation

ABSTRACT

Direct assessment of the kinetics of drum drying operation has been a difficult task as the mass and temperature profiles are hard to monitor. Still, developing better understanding of conductive drying would help to identify new operating windows for this technology. The drying kinetics was investigated by drying maltodextrin and starch suspensions with a novel custom-built laboratory-scale apparatus, which allows on-line monitoring of mass and temperatures. During drying, three separate periods were identified: the heating, the boiling and the conductive drying (declining rate) periods. The duration of the initial heating period was proportional to the film thickness and was responsible for a relatively small amount of water evaporated due to natural convection. During the boiling period, the drying rate kept constant while bubble formation impeded the heat transfer. Larger bubbles were observed for starch suspensions due to its viscoelastic properties. Thus, large temperature gradients between the heating pan and the film were observed for starch suspensions. During the conductive drying period, the initial amount of dry solids per surface area determines the drying rate as it determines the thickness of the semi-moist layer subjected to conductive drying. Application of a thin film is preferred to avoid boiling, especially at increasing solids content. This situation also better approaches double drum drying processes, where boiling occurs in the pool and conductive drying occurs on the drum.

1. Introduction

Drying is a widely applied technique in food industry to reduce moisture content and extend product shelf-life. Drying facilitates packaging, transportation and storage of foods by reducing weight and volume of the product (Qiu et al., 2018). Although many types of drying techniques exist, one can distinguish two main categories, i.e. convective and conductive drying technologies that rely on a different mode of heat transfer. Convective dryers, also known as direct dryers, constitute over 85% of the industrially applied dryers (Moses et al., 2014; Zarein et al., 2015). During convective drying the heat for evaporation is supplied by hot air, and contacted with the wet product to remove the moisture (Mujumdar, 2006). In contrast, during conductive drying heat is supplied through a (metal) wall (Devahastin and Mujumdar, 2006). Conductive dryers are more energy efficient compared to convective dryers, having a more efficient heat supply and lower energy loss via the exhaust gases (Devahastin and Mujumdar, 2006; Sahni and Chaudhuri, 2012). During conductive drying the product feed is usually applied as a thin wet film (Mujumdar, 2006). A potential disadvantage of conductive drying is that the product is dried at the boiling point, which is detrimental to heat sensitive products. This can only be alleviated by operating at reduced pressure to reduce the boiling temperature. Moreover, powders obtained from conductive drying have different properties such as bulk density and reconstitution behavior compared to those obtained with direct drying processes, such as spray drying (Caparino et al., 2012).

Different conductive dryer designs have been developed throughout the years, such as drum dryers, refractance window dryers and agitated thin film dryers (Fudym et al., 2003; Nindo and Tang, 2007; Pawar et al., 2011). Drum drying is frequently applied to dry pasty or viscous (food) materials, for example for drying starch, sodium caseinate, baby foods, mashed potatoes, fruit purees, and soup formulations. (Kalogianni et al., 2002; Rodriguez et al., 1996; Trystram and Vasseur, 1992). The influence of design and operating variables of conductive drying processes on product quality has been investigated especially for drum dryers, the most commonly applied conductive drying method.

Fritze (1973) compared the performance of different drum dryer designs during drying of gelatinized maize starch with varying combinations of feed concentration and drum speed. Kalogianni et al. (2002) used an industrial-scale double drum dryer to prepare pre-gelatinized maize starch and showed that in addition to the drying temperature, also the rheological and handling properties of the material are important in the drying process. Valous, Gavrielidou et al. (2002) examined the effects of the steam pressure, drum rotation speed and feed

---

* Corresponding author.
E-mail address: maarten.schutyser@wur.nl (M.A.I. Schutyser).

https://doi.org/10.1016/j.jfoodeng.2018.08.021
Received 25 May 2018; Received in revised form 18 July 2018; Accepted 20 August 2018

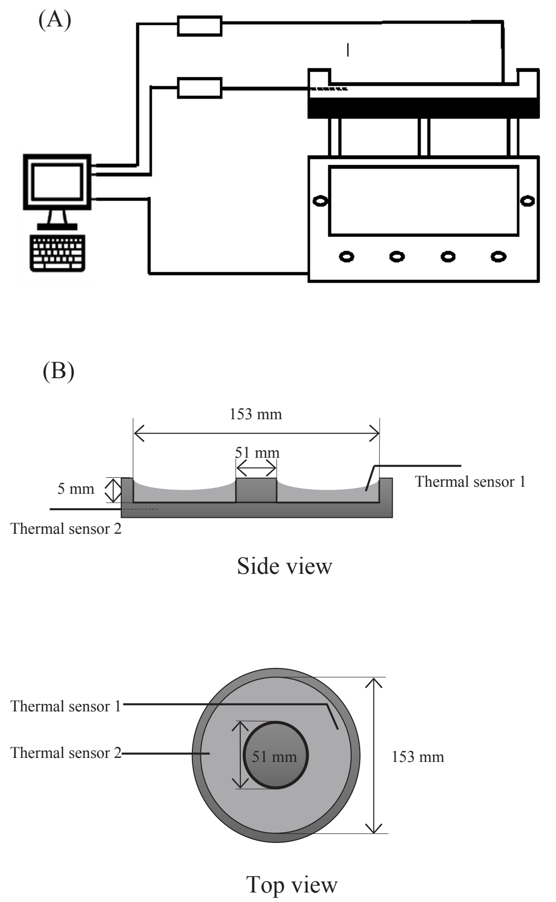

Fig. 1. Schematic drawing of (A) the system (B) Side and top views of the steel pan.

pool level, on the final moisture content and capacity during double drum drying of pre-gelatinized maize starch. Gavrielidou, Valous et al. (2002) measured the temperature profiles inside the feed pool of pre-gelatinized starch slurries and suggested that the heat transport in the pool is dominated by convection of flow currents induced by the rising bubbles. After pool boiling, the product is rolled into a wet film on the rotating drum wall. Depending on the conditions, the film is still boiling or is further dried by conductive drying. During conductive drying, the temperature of the film increases above the boiling point. A dry layer forms and grows, starting from the hot wall surface, until it encompasses the whole film. In this period the heat conduction of the dry layer limits the drying rate (Leniger and Beverloo, 2012). Apart from drum drying, other conductive thin film drying technologies have emerged, such as agitated thin film and refractance window drying (Nindo and Tang, 2007; Ochoa-Martínez et al., 2012; Pawar et al., 2011).

The previous studies, were conducted on pilot or industrial-scale equipment, and therefore could not accurately establish the transient drying kinetics. Only a few studies investigated the drying kinetics on laboratory scale. Fudym et al. (2003) used an experimental device to monitor the product temperature and thus the heat flux during contact drying, but did not measure the mass decrease as function of time. Karapantsios (2006) used a Simultaneous Thermal Analyzer to combine thermo-gravimetric and differential scanning calorimetry (DSC) measurements to record mass and product temperature during drying of starch, but the pan temperature was not registered, which is important to determine the heat flux during drying. Thus, the heat transfer between the hot pan and the product could not be well characterized. Therefore, to better understand the conductive drying processes, an in depth analysis of the drying kinetics is still necessary.

Therefore, the objective of this study was to unravel the transient drying kinetics of conductive thin film drying using an experimental system that allows simultaneous on-line monitoring of both mass and relevant temperatures. Potato starch and maltodextrin were chosen as representative model systems for conductive drying.

2. Materials and methods

2.1. Sample preparation

Maltodextrin suspensions with different solid concentrations (10%, 15% and 30% w/w total) were prepared by dispersing maltodextrin DE12 powders (Roquette, Hoofddorp, the Netherlands) into cold deionized water. The samples were mixed at room temperature for 1 h by a magnetic stirrer (IKA KMO2 basic, Staufen, Germany) with a mixing speed of 400 rpm, to ensure the homogeneity and dissolution. The suspensions were freshly prepared and used the same day.

Native potato starch was purchased from Merck KGaA (Darmstadt, Germany). Potato starch suspensions were prepared with different solids concentrations (5%, 10%, 15% and 40% w/w total) by adding native potato starch granule powders to cold deionized water in a glass beaker. The suspensions with low solid concentrations (5%–15%) were heat treated to gelatinize the starch according a procedure used by (Karapantsios, 2006). The suspensions were stirred (500 rpm) and heated to 80 °C for approximately 10 min (IKA C-MAG HS 7, Staufen,

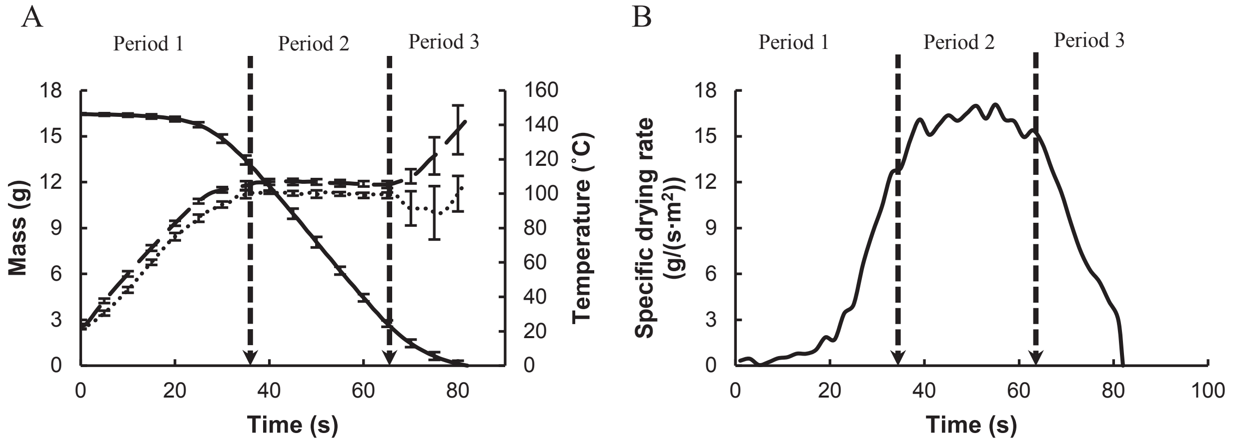

Fig. 2. (A) The mass (solid line) and temperature (dotted line) profiles of water and the temperature profile (dashed line) of the heated pan during the conductive thin film drying measurement (Film thickness = 1 mm). The curves represent the average of six independent measurements. The error bars show the standard deviation of the experimental data (n = 6); (B) specific drying rate curves versus time of the water film.