Journal of Food Engineering 173 (2016) 150–157

Contents lists available at ScienceDirect

Journal of Food Engineering

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

Effect of freezing pretreatment on the drying characteristics and volume change of carrots immersed in a fluidized bed of inert particles under reduced pressure

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A R T I C L E I N F O

Article history:
Received 7 September 2015
Received in revised form
4 November 2015
Accepted 6 November 2015
Available online 11 November 2015

Keywords:
Fluidized-bed drying
Vacuum drying
Freezing pretreatment
Carrot
Shrinkage

A B S T R A C T

A drying method with a low drying temperature and a high drying rate that induces small volume change in biological samples was developed for drying heat-sensitive foods and agricultural products. Freezing pretreatment was combined with fluidized-bed drying under reduced pressure. Cylindrical carrot samples were frozen and then immersed in a fluidized bed of inert particles under reduced pressure without thawing. A higher drying rate was achieved for carrots subjected to freezing pretreatment than for the untreated counterparts. The drying rate was higher at 12 kPa than at atmospheric pressure. The volume change induced during the drying process was smaller for carrots subjected to freezing pretreatment than for the untreated congeners. A high drying rate at a low temperature with minimal sample shrinkage was achieved via the combined freezing pretreatment and fluidized-bed drying under reduced pressure. This method can be applied for drying heat-sensitive materials such as food and agricultural products.

1. Introduction

The quality of a dried product is affected by the drying process employed. Heat-sensitive materials such as food and agricultural products must be maintained at a low temperature during drying. The drying methods that are generally applied to agricultural products include low-temperature hot-air drying and freeze-drying. Although low-temperature hot-air drying is a low cost process, a long drying time is required, and rotting or oxidation during drying are serious issues in the case of foodstuffs and sensitive chemical components. Freeze-drying induces porosity in the dried material, and some components of the drying medium remain in the dried material; moreover, the cost is very high and a long drying time is required (Kudra and Mujumdar, 2009). The development of drying technology employing a low drying temperature combined with a high drying rate and high energy efficiency (low cost) is required for drying heat-sensitive materials. Fluidized-bed drying under reduced pressure is expected to be an appropriate drying method for such materials. Fluidized-bed drying under reduced pressure is a lower cost technique with a significantly shorter drying time than required for freeze-drying, although the properties of the dried product obtained by using the former drying method are different from those of the same products obtained by freeze-drying (Tatemoto and Michikoshi, 2014).

Fluidized-bed drying is utilized in various fields such as food production and waste treatment. The drying rate in a fluidized bed is much higher than that of conventional hot-air drying (without a fluidized bed) because the heat and mass transfer on the surface of the material are much higher in fluidized-bed drying (Chandran et al., 1990; Wang and Chen, 2000; Ziegler and Brazelton, 1964). In the present study, relatively large materials that are difficult to be fluidized were considered as targets because achieving a shorter drying time is especially important for such materials. For relatively large materials, as mentioned above, fluidized-bed drying is impossible because of the difficulty of fluidization. A method in which the wet material is immersed in a fluidized bed containing fluidizing particles at atmospheric pressure has been proposed for

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http://dx.doi.org/10.1016/j.jfoodeng.2015.11.006
0260-8774/

Abbreviations and nomenclature

G	mass velocity of drying gas (kg/(m^2 s)
I	number of data points
i	data number
k	rate constant of Page's equation (s^{-1})
MR	moisture ratio (kg/kg)
n	dimensionless parameter of Page's equation (-)
P	pressure in drying chamber (Pa)
R	drying rate (kg-water/(m^2 s))
T_G	temperature in drying chamber (K)
T_{center}	temperature of carrot center (K)
t	time (s)
V	volume of carrot after drying (m^3)
V_0	volume of carrot before drying (m^3)
w	moisture content (kg-water/kg-dry solid)
w_e	equilibrium moisture content (kg-water/kg-dry solid)
w_0	initial moisture content (kg-water/kg-dry solid)
Subscripts	exp, experiment

drying these materials (Hatamipour and Mowla, 2002, 2003; Shirai et al., 1965; Sugiyama et al., 1974). This method may potentially be applied to materials with various shapes, such as spherical and cylindrical morphologies, etc.

To achieve low temperature drying, the process is often performed under reduced pressure. In the course of drying, the temperature of the material decreases with pressure. Under extremely low pressure, the rate of convective heat transfer from the drying gas to the material decreases. Therefore, thermal conduction, microwaves, and radiation are often used as heat sources. In this study, a fluidized bed is used to enhance the rate of heat transfer into the material being dried. For particulate materials, Kozanogle et al. (2002) and Kozanoglu et al. (2012) examined the drying characteristics in a fluidized bed under reduced pressure. The application of fluidized bed drying under reduced pressure to relatively large materials has only been reported in our previous papers (Tatemoto et al., 2005a, 2005b; 2007, 2004; 2015).

In the present study, a cylindrical carrot sample, representing a relatively large, wet material, was treated by immersion in a fluidized bed of inert particles (fluidizing particles) prior to drying. Carrot is a major agricultural product, and many researchers have examined its drying characteristics using different drying methods (for example, hot-air drying (Kaya et al., 2009)), microwave-vacuum drying (Cui et al., 2008; Nahimana and Zhang, 2011; Sumnu et al., 2005), freeze drying (Cui et al., 2008; Reyes et al., 2008), infrared drying (Kocabiyik and Tezer, 2009), fluidized and spouted-bed drying (Hatamipour and Mowla, 2002, 2003, Zielinska and Markowski, 2010, 2012), and low-pressure superheated-steam drying (Suvarnakuta et al., 2005, 2007). Hatamipour and Mowla dried a cylindrical carrot sample in a fluidized bed of inert particles at atmospheric pressure, and obtained a high drying rate compared with that of hot air drying (Hatamipour and Mowla, 2002, 2003). In one of our previous studies, we examined drying of disk-like carrot samples in a fluidized bed of inert particles under reduced pressure (Tatemoto and Michikoshi, 2014). Hot air (dry air) and superheated steam were used as drying gases. Under reduced pressure, superheated steam drying can be achieved at temperatures lower than 373 K because the boiling point of water is lowered. For fluidized bed drying under reduced pressure, a certain amount of gas is required for the fluidization process. Thus, scale-up is difficult because the load on the vacuum pump becomes high. By using superheated steam as the fluidizing gas (drying gas), it is possible to condense the gas at the exit of the fluidized bed, which decreases the load on the vacuum pump. Superheated steam drying under reduced pressure conditions without the use of a fluidized bed has been applied to food products by Suvarnakuta et al. (2005; 2007), and they reported that this drying method offers certain benefits for drying food products, including carrot.

In our previous study on drying disk-shaped carrot samples (Tatemoto and Michikoshi, 2014), a high drying rate was achieved at a low drying temperature (333 K) by using a fluidized bed of inert particles under reduced pressure (12 kPa), regardless of the type of drying gas (dry air or superheated steam) employed, although a higher drying rate was achieved with hot-air fluidized-bed drying than with superheated-steam fluidized-bed drying. Shrinkage of the dried carrot sample by the developed drying method was similar to that observed using conventional hot-air drying at low temperature. On this background, we suggest a drying method that combines freezing pretreatment and fluidized-bed drying under reduced pressure to maintain the size (volume) of the carrot sample during drying. Vacuum-freeze drying is currently utilized in the food industry as a method to maintain the size of dried materials; however, this technique has some disadvantages, as mentioned previously, including long drying time and high cost. Arolde and Fernanda (2007) evaluated the effect of freezing pretreatment on the drying time. They froze (and then thawed) select materials (carrot and pumpkin) and dried them in a conventional hot-air dryer. They reported that the pretreated materials required a shorter drying time than the untreated counterparts, although the volume change in the pretreated material during drying was almost equal to that in the untreated material. The present study adopts an approach in which frozen materials are immersed in a fluidized bed of inert particles under reduced pressure without thawing prior to the drying process. In the present method, evaporation and thawing may occur during drying, successively or simultaneously. There is no research on the drying of frozen materials in a fluidized bed of inert particles under reduced pressure.

This combination of freezing pretreatment and a fluidized-bed drying under reduced pressure was expected to afford a low drying temperature, high drying rate, and small volume change during the drying process for carrot samples, and the method should be applicable to the drying of heat-sensitive food and agricultural products. The effect of the freezing pretreatment on the drying characteristics and volume change in carrots during drying in the fluidized bed of inert particles under reduced pressure is examined herein.

2. Materials and methods

2.1. Drying apparatus and procedure

An outline of the experimental apparatus is presented in Fig. 1. A drying chamber was constructed from a glass tube with an inner diameter of 65 mm. A vacuum pump (oil-sealed vacuum pump, GLD-136C, ULVAC KIKO Inc.) along with a pressure-control valve was used to control the pressure in the drying chamber. The pressure was controlled at a reduced pressure of 12 ± 0.5 kPa. A pressure transducer (BARATORON®, Type 631, MKS Instruments, Inc.) and an indicator (indicator; Type 250, MKS Instruments, Inc.) were used to measure the pressure.

Dry, hot air and superheated steam were used as the drying gases. For the hot air treatment, dehumidified air was allowed to flow into a heater (electric furnace) and then into the fluidized bed. At the start of the experiment, the hot air was preheated by pumping into the fluidized bed at atmospheric pressure, and the bed temperature was controlled at the experimental temperature