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Effect of microwave air spouted drying arranged in two and three-stages on the drying uniformity and quality of dehydrated carrot cubes

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ABSTRACT

Microwave air spouted drying arranged in two and three-stages was used to improve the drying uniformity, energy efficiency and product quality (color, aroma, taste and rehydration capacity) of carrot cubes. The two and three-stage drying arrangements were designed making use of the information obtained from drying curves of single-stage microwave air spouted drying. The carrot cubes dried using the two and three-stage microwave air spouted drying had retention of color, chlorophyll and carotenoids contents and higher rehydration capacity. They also had better drying uniformity in terms of moisture content, product temperature and sample size. The two and three-stage drying arrangements had significantly higher material loading capacity and energy utilization ratio. The carrot cubes dried using these two drying arrangements had better flavor and taste after drying as well as after rehydration. Thus the two and three-stage arrangements had advantages over single-stage microwave air spouted drying in terms of product quality and energy efficiency.

1. Introduction

Drying is one of the oldest and the most commonly used methods of preservation of fruits, vegetables and aquatic products as it lowers water activity and extends shelf-life (Zhang et al., 2006). Drying is also regarded as the most energy and time consuming process when applied to food materials as they have low thermal conductivity (Ratti, 2001). Different drying methods are used to dry different food materials; however, each drying technique has its own advantages and drawbacks. Many conventional drying methods such as hot air, vacuum, and freeze-drying result into low drying rates, especially in the falling rate period of drying (Clary et al., 2005). The long drying times at relatively high temperatures prevailing during the falling rate period often lead to undesirable thermal degradation of the dried products.

In order to address the limitations of conventional drying methods, new drying methods and dryers with new heating source have been investigated and developed in last few decades. Microwave is more efficient and more broadly applied among these novel technologies. The absorption of microwave energy can make polar molecules (water, fat, carbohydrates, alcohol etc.) change their position and generate heat. Water in food is the primary component responsible for dielectric heating. Due to their dipolar nature, water molecules attempt to follow the electric field which alternates its direction at very high frequencies. Such rotations of the water molecules generate heat (Zhang et al., 2010). There is an increased interest in application of microwave in drying of fruits and vegetables and the findings of many of such studies have been reported. Khraisheh et al. (2004) evaluated the retention of ascorbic acid in potatoes dried using microwave and convective drying. Potatoes dried under microwave radiation retained much higher amount of ascorbic acid as compared with air-dried samples. Askari et al. (2006) studied the effect of hot air and microwave drying on the rehydration characteristics of apple slices. The rehydration rate of air-dried, freeze-dried and microwave-dried apple slices was 4.04, 4.84 and 6.76, respectively. Alibas (2007) studied the efficacy of hot-air, microwave and combined hot air-microwave drying methods on pumpkin slices and showed that the energy consumption in the combined hot air-microwave drying was the lowest among these three drying methods. Soysal (Soysal et al.,

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2006) studied the kinetics and energy consumption during the microwave drying of parsley leaves. They showed that the Midilli et al. (2007) model fitted the moisture history data and predicted the drying rate data quite accurately. They also showed that the increase in the sample loading to an appropriate range improved the drying efficiency.

Despite the fact that the microwave assisted drying provides higher drying rate and energy efficiency compared to the conventional hot air drying; however, the non-uniformity in drying caused by uneven spatial distribution of the electromagnetic field inside the drying chamber still remains one of the most important limitations in microwave drying process (Yan et al., 2010). This non-uniformity leads to hot and cold spots within the dried products and negatively impacts the quality of the dried product and also raises the food safety concerns (Vadivambal and Jayas, 2008). Currently there are two approaches to address the non-uniformity issue encountered in microwave-assisted drying: 1) improving the uniformity of electromagnetic field in the microwave cavity; 2) improving the absorption uniformity of microwave energy by causing the physical movement of the material within the microwave cavity (Li et al., 2011). The second approach is more effective than the first in enabling inform absorption of microwave energy by the samples. When the sample is randomly or systematically moved or displaced during drying, the uniformity of drying can be significantly improved. Such a movement can lessen the dependence on the uniformity of distribution of electromagnetic field and the time/space-averaged microwave energy absorption can be considered to have the same probability. For example, the uniformity of microwave heating can be significantly improved by combining it with spouted bed or fluidized bed if the material to be dried is of particulate nature. Kaensup et al. (2002) designed and used a microwave-vacuum-rotary drum dryer in which the particulates moved and mixed well as the drum rotated, which effectively overcame the uneven distribution of electromagnetic field. Experiments with red chili showed that the rotation of the drum in this dryer produced high quality dried product; while, the chili sample was thermally deteriorated when the drum was not rotated. Feng and Tang (1998) dried apple slices in a microwave-spouted bed dryer to determine uniformity of temperature in the apple slices and the quality of the dried product. The results showed that the combination of the microwave irradiation with spouting reduced the drying time by 88%. Due to the unique hydrodynamics of the spouted bed, the slices were effectively mixed and the spatial temperature variation remained within ±1.4 °C during most of the drying and reached ±4 °C at the final drying stage. The microwave-assisted spouted bed dryer was applied by Liu et al. (2012) in drying potato-based snacks food and produced dried products with better texture, color and dehydration ability. The efficacy (in terms of rehydration and texture) of the microwave-assisted spouted bed drying was compare with other methods, such as hot-air drying and microwave vacuum drying (Mothibe et al., 2014; Zhang et al., 2012). The above research indicates that the microwave-assisted fluidized or spouted bed drying is effective method in minimizing the uneven heating associated with dryers using microwave energy.

In the above context, the objectives of this study were to (1) design two-stage and three-stage microwave air spouted drying arrangements which would achieve better drying uniformity, increase energy efficiency and improve product quality; (2) investigate the quality and characteristics of carrot dried and rehydrated cubes obtained from these two and three-stage drying arrangements; (3) study the drying uniformity of samples of obtained from these drying systems.

2. Materials and analysis methods

2.1. Materials

Carrots were purchased from a local supermarket in Wuxi, China. They were washed, peeled, sliced to cubes of $9 \times 9 \times 9$ mm^3, then blanched in a water-bath at 95°Cfor 5 min. The blanched samples were immediately cooled in chilled water to avoid over processing and the water was subsequently drained water. The initial moisture content of the blanched samples was 14.87(±0.03) g/g dry solids.

2.2. Drying experiments

A laboratory-scale microwave air spouted dryer, developed at State Key Laboratories of Food Science and Technology was used for drying the carrot cubes. A schematic diagram of the two and three-stage drying arrangements is shown in Fig. 1. The system consists of the following four basic components: (1) a cylindrical multimode microwave cavity (stainless steel, 40 cm outer diameter and 200 cm height), (2) three microwave generators (at 2450 MHz) distributed symmetrically along the microwave cavity height, (3) a pulse-spouted system, a pressure compressor providing the required pulsed air flow, (4) a control system.

This system of two and three-stage drying was comprised of different numbers of microwave chambers. In the case of three-stage drying, the drying system was comprised of 7 microwave chambers were arranged in three stages shown schematically in Fig. 1. The first, second and third stages contained four, two and one microwave chambers, respectively. The same amount of material was loaded in each chamber during microwave drying. When the samples were dried in all the four microwave chambers of the first stage for a given length of time, they were mixed and transferred to the two microwave chambers of the second stage. Finally, the samples from the second stage were transferred to the third stage which contained only one microwave chamber. The two-stage drying system contained three microwave chambers, two in the first stage and one in the second stage, respectively. The efficacy of these two microwave drying systems was compared with microwave air spouted drying system which had only one microwave chamber.

The carrot cubes were dried using above mentioned drying systems until the final moisture level was below 0.1 (g/g, d.b). The original weight of blanched carrot cubes for drying is 400 g. The microwave power in the case of the microwave spouted bed dryer was maintained at 800 W. An air compressor was used to provide the required pulsed air at ambient temperature (25 °C). The spouting was operated in a cycle of open for 2 s and close for 4 s. The hydrodynamic motion of the sample in the drying cavity was achieved by using this pulsed air flow. The velocity of air flow was determined as a function of the height of the material in the bed.

2.3. Determination of moisture content

Moisture content of the samples was measured using the oven method (GB/T8858-88, National Standard of China). The samples were dehydrated in an oven at 105 °C until they achieved their constant mass. The mass values of each sample before and after dehydration were measured gravimetrically. The moisture content of samples was calculated by using equation (1):

$$x_t = \frac{m_t - m_d}{m_d} \tag{1}$$

where, x_t is the moisture content at time t on dry basis (g/g, d.b), m_t