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ORIGINAL PAPER

Effect of a Modified Atmosphere on Drying and Quality Characteristics of Carrots

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Abstract Many quality degradation problems are related to the high O_2 content of normal air atmosphere during drying. To reduce O_2 content in drying atmosphere and obtain food products with high quality, modified atmosphere drying was conducted. In this study, carrots were used as experimental materials to investigate the effects of drying parameters on the drying characteristics and product quality. Results showed that the increase in drying temperature and the decrease in O_2 content positively influenced drying rate and effective moisture diffusivity. High carotenoid content, ascorbic acid retention ratio, and rehydration ratio were produced with low drying temperature and O_2 content. The color parameters of products were highly correlated with carotenoid content, and low color difference could be achieved as drying temperature and O_2 content decreased. Drying temperature and O_2 significantly influenced carotenoid content, ascorbic acid content, rehydration, and color difference of dried products. Good quality parameters were obtained only at low drying temperature under the drying condition of normal atmosphere and could be achieved at drying temperatures of 40 to 70 °C when O_2 content is 5 %. Therefore, the modified atmosphere drying is a promising method to protect the quality of dried products.

Keywords Modified atmosphere drying · Carrot · Drying characteristics · Product quality

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Nomenclatures

a^*	Redness
b^*	Yellowness
C_d,C_0	Ascorbic acid contents of dried carrots and fresh carrots
D_{eff}	Effective moisture diffusivity (m^2/s)
L	Half thickness of carrot slice (m)
L^*	Lightness
M	Moisture content (g/g dry base)
M_0	Initial moisture content (g/g dry base)
M_e	Equilibrium moisture content (g/g dry base)
t	Drying time (s)
W	Mass of carrot slices (g)
W_d	Mass of dry matter in carrot slices (g)
W_p	Weight of samples before rehydration experiments (g)
W_{RR}	Weight of samples after rehydration experiments (g)
X_1	Drying temperature degree Celsius
X_2	O_2 content
ΔE	Color difference

Introduction

Hot-air drying is one of the most common drying methods used for food materials, but this method possesses many disadvantages, such as low energy efficiency and lengthy drying time during the falling rate period (Yongsawatdigul and Gunasekaran 1996; Maskan 2001). This drying method may also lead to serious and undesired quality degradation in terms of physical or component quality; therefore, product quality is markedly decreased. The presence of O_2 during conventional hot-air drying is one of the important factors that cause product quality deteriorations, such as color fading, browning, and nutrient component loss (Anderson and Lingnert 1997). Substituting O_2 with inert gas is a promising and effective method to restrain chemical and microbiological reactions, protect nutrient components, and improve product quality (O'Neill et al. 1998).

Inert gases, such as N_2 and CO_2 gases, can be used to replace O_2 to reduce browning, increase product porosity, and shorten drying period (O'Neill et al. 1998); Ramesh et al. (1999, 2001) also stated that inert gas drying with N_2 increases the drying rate, mass and heat transfer, and retention of nutrient components, such as vitamin C and carotenoid. Hawlader et al. (2006a) combined heat pump drying technology with inert environmental conditions, producing a modified atmosphere heat pump drying method. Several fruits and vegetables, including apple, guava, and potato, have been dried using this method; the color protection and nutrient retention of the products dried with inert gases (N_2 and CO_2) are similar to the products dried by vacuum or freeze drying; this result indicates that the modified atmosphere heat pump drying can protect the overall quality of products (Hawlader et al. 2006a, 2006b, 2006c). Doungporn et al. (2012) developed a mathematical model to describe the drying behavior of paddy in modified atmosphere drying. Corrêa et al. (2012) investigated convective drying of unripe, ripe, and overripe banana at the atmosphere modified with ethanol, and found that higher diffusivity was obtained with the surface use of ethanol, followed by the modified atmosphere and the normal atmosphere in this order.

Carrot is one of the important vegetables grown worldwide (Sumnu et al. 2005). This vegetable is also one of the most commonly consumed foods for human nutrition because of its high vitamin content and carotenoid content (Doymaz 2004). Convective drying is a conventional method to remove the water content of carrot (Zogzas et al. 1994; Doymaz 2004; Kumar et al. 2012). To improve product quality or increase drying rate of carrot, several new technologies are applied, such as infrared drying (Togrul 2006), microwave drying (Arikan et al. 2012), infrared-assisted convective drying (Mihoubi et al. 2009), microwave-assisted convective drying (Prabhanjan et al. 1995), ultrasound-assisted convective drying (Carcel et al. 2011), microwave vacuum combined freeze drying (Cui et al. 2008), and the combination of freeze-drying, microwave heating, and air or vacuum drying (Litvin et al. 1998).

The oxidation of food ingredients, such as vitamins and pigments, is one of the most important causes of quality loss during food processing (Anderson and Lingnert 1997). Ascorbic acid and carotenoid are the main vitamin and pigment in carrot, respectively; these substances are easily oxidized during drying under normal atmosphere (Lin et al. 1998; Leong and Oey 2012). Thus, the drying of carrot under low O_2 content is a considerable way to lower the oxidative effects. Ramesh et al. (1999) studied the drying rate, mass and heat transfer coefficients, total carotenoids, and vitamin C contents of blanched carrot with inert gas drying and compared with conventional hot-air drying. The drying characteristics and quality factors of the modified atmosphere drying of carrot at different drying temperatures and O_2 contents, however, need further study and detailed discussion. Modified atmosphere drying with low O_2 content has been proven to be beneficial to the rehydration, color, and other important quality parameters of dried foods, including apple, guava, and potato (Hawlader et al. 2006a). However, little information is available regarding the effects of O_2 content of modified atmosphere drying on the rehydration quality and color of carrot products.

This research aimed to investigate the influence of modified atmosphere drying on the characteristics and quality of carrot slices by using a self-developed modified atmosphere dryer. N_2 gas was chosen as inert gas to replace some portion of air and control O_2 content in the drying atmosphere during drying process. The effects of temperature and O_2 content on drying characteristics, including effective moisture diffusivity and quality parameters, such as carotenoid content, ascorbic acid content, color change, and rehydration ability, were discussed.

Materials and Methods

Materials

Fresh, ripe carrots were provided by a local Danis supermarket in the province of Henan, China, and were stored in a refrigerator at 2 to 4 °C. Before experiment, carrots with 30±1 mm diameter were sliced into 5 mm thick using a food slicer (Helian Co., model MC30, China). The thickness of each slice was measured using a vernier caliper (Guanglu Co., model GL150, China). The carrot slices were dried immediately after cutting. The initial moisture content of the carrot slices was determined by vacuum drying at 70 °C for 24 h (AOAC 1990). The initial moisture content of the fresh samples was measured in triplicate and was determined as 8.46±0.25 g/g (dry base).

Modified Atmosphere Dryer

The photo and schematic of the modified atmosphere dryer equipped with a heat pump system and an air recirculation drying system are presented in Figs. 1 and 2, respectively. The dryer was designed and manufactured by Henan University of Science and Technology and Guangdong Agri-machinery Research Institute. The heat pump system included a reciprocating compressor, an evaporator, an internal condenser, an external condenser, and an expansion valve. R22 refrigerant was used for the heat pump system. The air recirculation

Fig. 1 Photo of the modified atmosphere dryer

drying system included a drying chamber, a main air blower, an auxiliary air blower, a dehumidification air blower, an auxiliary electric heater, an inert gas cylinder, and a material trolley.

The refrigerant is compressed by a compressor to produce fluid with high pressure and temperature. When the refrigerant influxes the internal condenser, thermal energy transfers from high-temperature refrigerant to the modified air in the drying chamber through the condenser pipe wall. The refrigerant with low temperature flows through the expansion valve to reach low pressure. The refrigerant then flows into the evaporator and the compressor to achieve high temperature and pressure, and a new circulation proceeds. The two condensers are installed for better controlling the drying temperature of the modified drying air.

The modified air in the chamber is heated by the internal condenser and flows into the chamber by the force of the two air blowers with high temperature. The auxiliary heater is installed to further adjust gas temperature when necessary. The air then flows through an air deflector and air distribution plates into the material trolley. After heat and mass exchange with materials, the air with high humidity flows through the evaporator to decrease the temperature lower than the dew point. Excessive vapor condensates and is detached as a form of liquid. The liquid is then removed from the dryer through a drainage pipe, and the gas with low humidity flows through the internal condenser to increase the temperature for the next cycle of drying. The dehumidification air blower is switched on only under the following conditions: the air is flushed out with N_2 gas at the beginning of drying in each experiment, and the heat pump system fails to reach the humidity removal requirement of the evaporator during drying.

N_2 is aerated to substitute the air in the chamber from an N_2 gas cylinder. The O_2 content is detected by two O_2 sensors (Yonglian Co., model GYH25, China) inside the chamber and is controlled by the valve in front of the N_2 cylinder. The drying temperature in the chamber is measured by K-type thermocouples. Gas velocity is measured using a hot bulb anemometer (NOKI Co., model QDF3, China). The relative

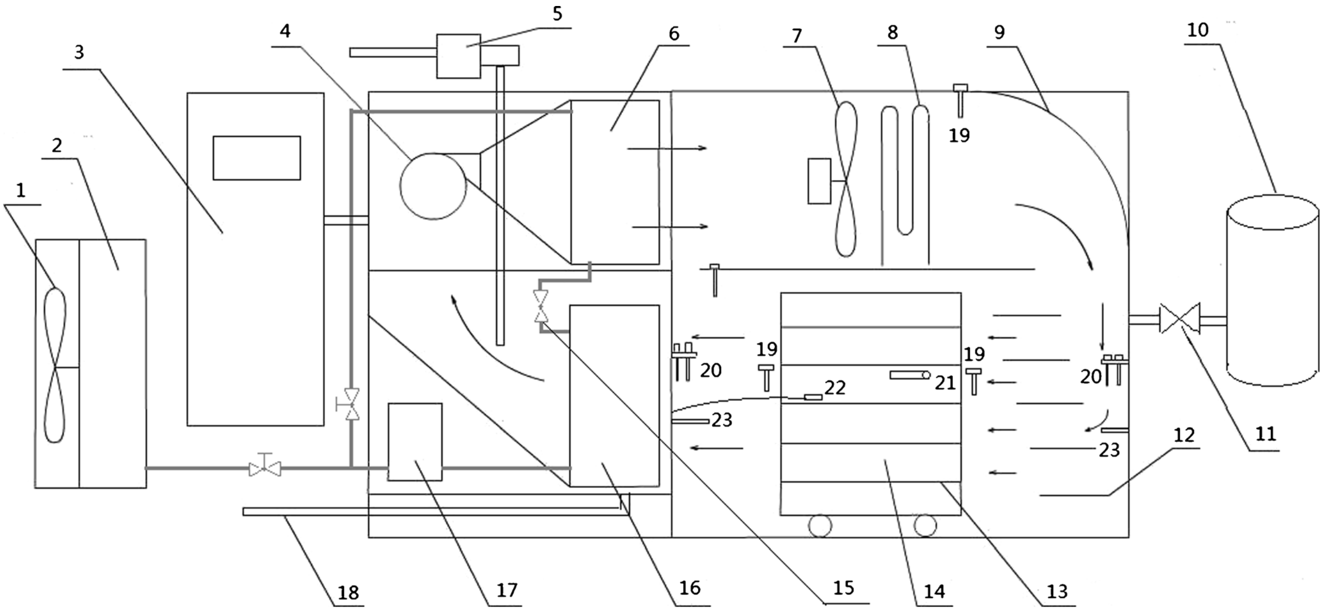

Fig. 2 Schematic of the modified atmosphere dryer. *1*, External fan; *2*, external condenser; *3*, control panel; *4*, main air blower; *5*, dehumidification air blower; *6*, internal condenser; *7*, auxiliary air blower; *8*, auxiliary heater; *9*, air deflector; *10*, inert gas cylinder; *11*, control valve; *12*, air distribution plates; *13*, sample tray; *14*, trolley; *15*, expansion valve; *16*, evaporator; *17*, compressor; *18*, drainage pipe; *19*, thermocouple; *20*, O_2 sensor; *21*, anemometer; *22*, thermal sensor; *23*, hydrometer

humidity of the drying gas is monitored by two hygrometers (Weiwang Co., model BS8904, China).

All drying controls are operated with the operation panel, and all the parameter values are displayed on the panel screen.

Experimental Methods

N_2 gas was flushed into the modified atmosphere dryer to adjust the O_2 content of the drying gas inside the drying chamber. The heat pump system was run to control the drying temperature and humidity. The carrot slices with 500 g weight were uniformly spread on a tray to separate from one another and then placed into the drying chamber. The chamber door was closed immediately. The modified atmosphere drying experiments were conducted at drying temperatures of 40, 50, 60, and 70 °C and with O_2 contents of 5, 10, 15, and 20.9 % (normal air). The average inlet humidity of hot air at 40, 50, 60, and 70 °C was approximately 21.3, 15.1, 10.5, and 6.8 %, respectively. The average inlet relative humidity of the modified hot air with 5 % O_2 content at 40, 50, 60, and 70 °C was approximately 14.5, 11.7, 8.6, and 6.3 %, respectively. The mass changes of the carrot slices were measured with an electric balance (Zhifu Co., model DJ2000, with a precision of 0.1 g, China) and recorded every 20 min. To minimize the influence of mass measurement on the drying condition, the weighting operation was conducted by two persons cooperatively and rapidly. The chamber door was opened, and the sample tray was removed for weighting immediately. After weighing, the tray was returned on the original place and the chamber door was closed promptly. As the weighing operation consumed less than 15 s, no significant disturbances were imposed on the steady-state drying operation. All the operating parameters, including O_2 content and drying temperature, recovered to the setting values within 30 s generally. The drying was ended when the continuous two records unchanged. The final moisture content of the product was 0.06±0.01 g/g (dry base). All experiments were performed in triplicate. The mean values are reported and used for further work.

The moisture content of the carrot slices can be calculated using the following equation (Sharma et al. 2005):

$$M = \frac{W - W_\mathrm{d}}{W_\mathrm{d}}, \tag{1}$$

where W is the mass of the carrot slices (g), W_d is the mass of the dry matter (g), and M is the moisture content (g/g, dry base).

Effective Moisture Diffusivity

The dimensionless moisture ratio (MR) can be obtained as follows (Midilli 2001):

$$\mathrm{MR} = \frac{M - M_\mathrm{e}}{M_0 - M_\mathrm{e}}, \tag{2}$$

where M_0 is the initial moisture content (g/g, dry base) and M_e is the equilibrium moisture content (g/g, dry base).

Assuming the main mechanism exhibits diffusive nature, the experimental data for the determination of diffusivity were interpreted using Fick's second diffusion equation. The analytical solution of Fick's equation in slab geometry by assuming uniform initial moisture distribution is as follows (Crank 1975):

$$\mathrm{MR} = \frac{M - M_\mathrm{e}}{M_0 - M_\mathrm{e}} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_\mathrm{eff} t}{4L^2} \right) \tag{3}$$

where D_eff is the effective moisture diffusivity (m^2/s), t is the drying time (s), and L is half thickness of thin layer of sample slice (m).

The D_eff values were obtained through nonlinear numerical calculation with Statistica 10.0 software (Statsoft Co., Tulsa, USA), with the first five terms of Eq. (3) (Corrêa et al. 2012).

Carotenoid Content

The carotenoid extraction and analysis were conducted using the method of Ma et al. (2008). The carotenoid content was expressed as milligram carotenoid per 100 g carrot on dry basis. All determinations were conducted in triplicate. The mean value for fresh carrot was 46.2 mg carotenoid/100 g carrot.

Ascorbic Acid Retention Ratio

The ascorbic acid content was measured in fresh and dried carrot samples by titration using 2,6-dichlorophenol-indophenol, as described in the Official Methods of Analysis (AOAC 1984). All analyses were conducted in triplicate. The ascorbic acid content was expressed as milligram ascorbic acid per 100 g of carrot on dry basis. The mean value for fresh carrot was 36.5 mg/100 g carrot.

The ascorbic acid retention ratio (AARR) of dried carrots was calculated as follows:

$$\mathrm{AARR} = \frac{C_\mathrm{d}}{C_0}, \tag{4}$$

where C_d and C_0 are the ascorbic acid contents of dried carrots and fresh carrots, respectively.

Color Measurement

The color of the carrot slices was measured with a colorimeter (Datacolor Co., model Datacolor100, USA). For each slice, five different points were measured to capture lab values, including lightness (L^*), redness (a^*), and yellowness (b^*). The average of the five readings was calculated. The changes in the individual color values were calculated as follows:

$$\Delta L = L^* - L^*_0, \quad \Delta a = a^* - a^*_0, \quad \Delta b = b^* - b^*_0, \tag{5}$$

where the subscript 0 refers to the color reading of fresh carrot slices, which were used as the reference. The total color difference (ΔE) was determined using the following equation:

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2}. \tag{6}$$

Higher ΔE value represents greater color change of the reference material.

Rehydration Ratio Measurement

Five grams of samples was weighed and placed into 200 mL beakers. Water with 60 °C temperature was poured into the beakers. The beakers were immediately placed into a constant-temperature water bath (Huanyu Co., model HH-8, China), which can maintain rehydration temperature at 60 °C. The rehydration experiments were conducted for 30 min. The samples were then removed from the beakers. The excess water on the sample surface was removed with tissue paper rapidly, and weighting was performed using a digital balance (Yinghua Co., model BNT-A, with a precision of 0.001 g, China). Rehydration ratio (RR) was calculated as follows:

$$\mathrm{RR} = \frac{W_{\mathrm{RR}}}{W_{\mathrm{p}}}, \tag{7}$$

where W_{RR} and W_{p} are the weight of samples after and before rehydration experiments (g), respectively.

Each experimental run was performed in triplicate. The mean values of RR were calculated and recorded.

Statistical Analysis

Data were analyzed statistically by Data Processing System 3.0 software (Ruifeng Co., China). The analyses of variance (ANOVA) were conducted by ANOVA procedure. Mean values are considered significantly different when p value is lower than 0.05.

Results and Discussion

Drying Characteristics

The drying curves of the modified atmosphere drying of carrot at different drying temperatures are shown in Fig. 3. The O_2 content and gas flow rate were 5 % and 1 m/s, respectively. The drying time decreased with the increase of drying temperature during the modified atmosphere drying under low O_2 content condition. The drying times required to reach the final moisture content of samples when the O_2 content was 5 % were 600, 390, 340, and 250 min at drying temperatures of 40, 50, 60, and 70 °C, respectively. Increasing the drying temperature produces more thermal flux from drying medium to samples, enhances water diffusion and evaporation, and speeds up drying. Furthermore, the increase in drying temperature reduces the relative humidity of drying air, improves the vapor pressure difference between materials and drying medium, and increases the moisture flux rate from materials into drying air. The influence of drying temperature on drying rate during the modified atmosphere drying with low O_2 content is identical with that in conventional hot-air drying, which has been reported and interpreted in literature (Doymaz 2004; Dev et al. 2011; Purkayastha et al. 2013).

The drying curves of the modified atmosphere drying of carrot with different O_2 contents are shown in Fig. 4. The drying temperature and gas flow rate were set as 50 °C and 1 m/s, respectively. The drying rate at low O_2 content is slightly higher than that at high O_2 content. When N_2 gas is flushed to substitute some portions of conventional hot air to

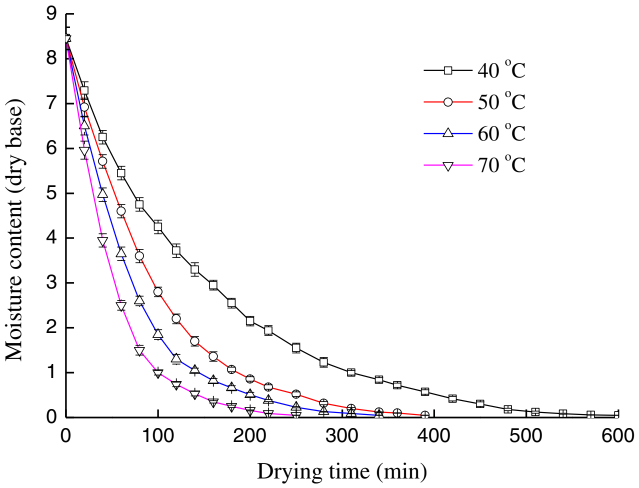

Fig. 3 Drying curves of the modified atmosphere drying of carrot at different temperatures with 5 % O_2 content

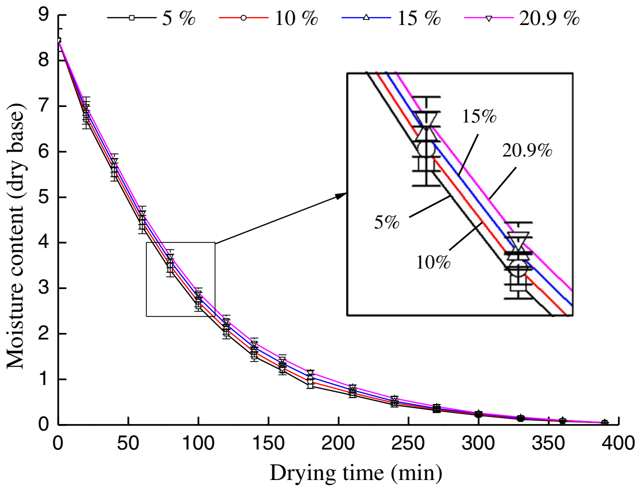

Fig. 4 Drying curves of the modified atmosphere drying of carrot with different O_2 contents at a drying temperature of 50 °C

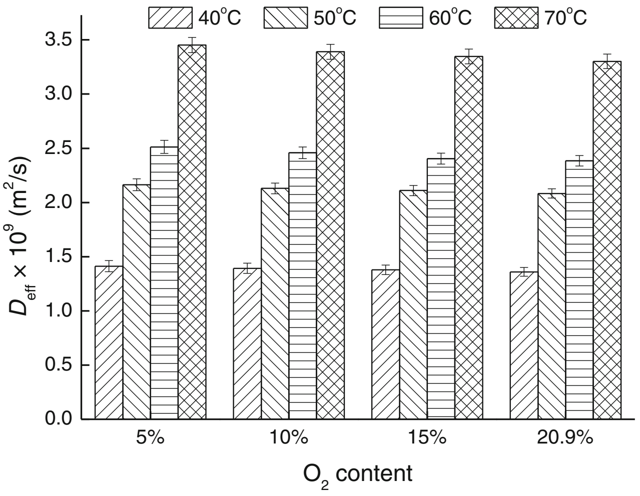

Fig. 5 Effective moisture diffusivity values of carrot by the modified atmosphere drying

reduce O_2 content, a part of vapor in the drying air is removed simultaneously, which reduced the vapor pressure and relative humidity of drying air. For example, by aerating N_2 gas during drying, the relative humidity values of the drying medium in the drying chamber at a drying temperature of 60 °C are approximately 10.5, 9.8, 9.1, and 8.6 % when the O_2 contents are 20.9, 15, 10, and 5 %, respectively. Drying at lower relative humidity provides higher driving force for moisture inside materials to move toward the surface and into drying air. Therefore, the decrease of O_2 content in the modified atmosphere drying reduces the relative humidity of drying medium and increases the diffusion gradient between materials and drying medium, which may be the main reason of the increase in drying rate. Ramesh et al. (2001) reported that the heat and mass transfer coefficients of the inert gas (N_2) drying of spice paprika are higher than those of normal hot-air drying. They concluded that the inert gas drying using N_2 gas can achieve higher moisture diffusivity and drying rate compared with conventional hot-air drying. Hawlader et al. (2006b) also stated that inert gas drying shows an improved effective diffusivity and higher drying rate compared with the drying with normal air as drying medium. Therefore, decreasing O_2 content has positive and limited effects on shortening drying time.

D_{eff} values of carrot obtained at different drying temperatures and O_2 contents are shown in Fig. 5. D_{eff} values were from 1.3596×10^{-9} to 3.4526×10^{-9} m^2/s, which lie within the general range of 10^{-12} to 10^{-8} m^2/s for the drying of food materials (Zogzas et al. 1996). D_{eff} values increased greatly with increasing drying temperature and increased slightly with reducing O_2 content, which is consistent with the illustration mentioned above about the effects of drying temperaure and O_2 content on heat and mass transfer. The O_2 gas in drying air could influence the physical property of material surface or cause more microscopic capillary shrinkage and less porosity on the surface (Hawlader et al. 2006a) and increase mass transfer resistance during drying. Hence, the reduction of O_2 content has an insignificant positive influence on D_{eff} value. Ramesh et al. (1999, 2001) concluded that the drying of several materials, such as carrot and potato, under inert gas increased the drying rate and D_{eff} value compared with normal air drying, which is similar to the result in this study. However, Doungporn et al. (2012) stated that the drying rates in drying paddy with normal air and inert gas are the same. This difference could be due to the different moisture contents of materials. The materials in the reports of Ramesh et al. (1999, 2001) and Hawlader et al. (2006b) have high moisture contents, and their drying process has a constant rate period. Therefore, the physical and thermal properties of different drying gases could affect the drying rate and D_{eff} value, especially in the initial period of drying. The moisture content of paddy in the report of Doungporn et al. (2012) is 32 % (dry base), and the physical and chemical properties of samples are the major control element that affects moisture diffusion and removal (Pan et al. 2007). So, the effect of the drying gas property on the drying rate of paddy is thus negligible. Different O_2 contents lead to different density, specific heat capacity, viscosity, and thermal conductivity of drying gas and therefore affect the heat and mass transfer of high moisture materials in hot-air drying. Carrot is a material with high moisture content; hence, the change in its drying rate and D_{eff} value under different drying airs is similar to that in the materials reported by Ramesh et al. (1999, 2001) and Hawlader et al. (2006b).

D_{eff} values in this study are close to the values of 2.74 to 4.64×10^{-9} m^2/s reported for the hot-air drying of carrot pomace at 60 to 75 °C (Kumar et al. 2012), 0.776 to 9.335×10^{-9} m^2/s for the convective drying of carrot slices at 50 to 70 °C (Doymaz 2004), 1.257 to 2.200×10^{-9} m^2/s for the hot-air drying of carrot at 35 to 55 °C (Kaya et al. 2009), and

1.371×10^{-9} m^2/s for the hot-air drying of carrot slices at 60 °C (Markowski 1997). D_{eff} values in this study are also comparable with the reported values of 15.33 to 28.85×10^{-10} m^2/s for the inert gas drying of paprika (Ramesh et al. 2001).

Carotenoid Content

The influences of the drying temperature and O_2 content of the modified atmosphere drying on carotenoid content are shown in Fig. 6. The values of carotenoid content ranged from 15.02 to 37.18 mg/100 g in this study. Carotenoid content value increased apparently with the decrease of O_2 content and drying temperature. Carotenoid content is an important indicator in determining the final quality of dried carrot products. When carotenoid is present in intact plant tissue, the quality of carotenoid is stable. However, when drying is conducted, the carotenoid inside the materials is isolated and is vulnerable to the effects of processing conditions, such as heat and high O_2 tension (Klieber and Bagnato 1999), mainly because of oxidation and destruction of the conjugated double bonds in the carotenoid molecules. Carotenoid content decreased at approximately 37, 21, 31, and 24 % when the drying temperature increased from 40 to 70 °C and the O_2 contents were 20.9, 15, 10, and 5 %, respectively. Carotenoid is easily degraded and isomerized at high temperature (Cui et al. 2004). The increase in drying temperature could therefore accelerate the oxidation reaction of carotenoid, and the drying of carrot at low temperature is beneficial to protect carotenoid. Saxena et al. (2012) also reported that the degradation rate of total carotenoid increased as the drying temperature increased. The carotenoid content values of products dried with 5 % O_2 content were 54, 80, 72, and 86 % higher than those dried under conventional hot-air atmosphere when the drying temperatures were 40, 50, 60, and 70 °C, respectively. Modified atmosphere drying with low O_2 content can reduce the contact probability between O_2 and carotenoid, prevent carotenoid oxidation, and reduce carotenoid loss. Hence, the reduction of O_2 content during drying is helpful to reach high carotenoid retention. Ramesh et al. (1999) stated that the total carotenoid content of carrot and paprika dried under inert gas condition is obviously higher than that of the samples dried under normal air condition and that drying with inert gas instead of normal air could effectively prevent carotenoid oxidation.

The values of carotenoid content in this study are comparable with the reported values of 40 mg/100 g for β-carotene in the freezing drying of carrot and 30 mg/100 g to 36 mg/100 g in vacuum drying at 40 to 80 °C (Wu et al. 2013). The modified atmosphere drying can therefore protect carotenoid similar to freezing and vacuum drying. This comparison result is similar to the conclusion of Hawlader et al. (2006a).

Ascorbic Acid Retention Ratio

The influences of drying temperature and O_2 content on ascorbic acid retention ratio in the modified atmosphere drying are shown in Fig. 7. Ascorbic acid retention ratio increased by reducing O_2 content and decreasing drying temperature. As a thermal- and O_2-sensitive material, ascorbic acid is easily destroyed under the conditions of high drying temperature and high O_2 content (Davey et al. 2000). Under aerobic conditions, ascorbic acid is easily oxidized to dehydroascorbic acid during drying process, followed by hydrolysis and further oxidation (Santos and Silva 2008). Decrease in O_2 content in drying atmosphere would reduce the contact probability between ascorbic acid and oxygen molecules. So the ascorbic

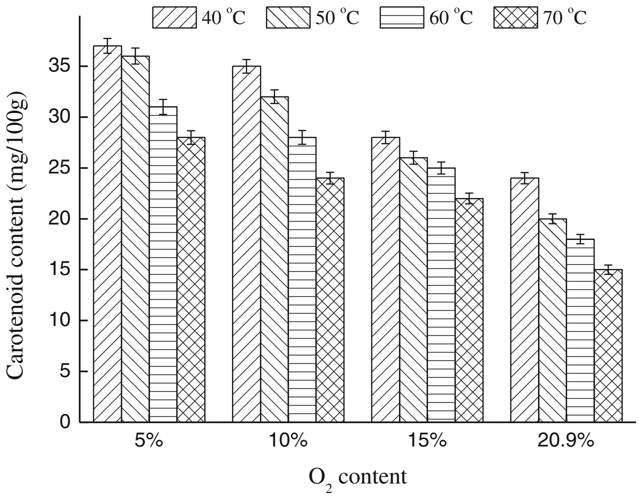

Fig. 6 Carotenoid content of dried carrot at different drying temperatures and O_2 contents

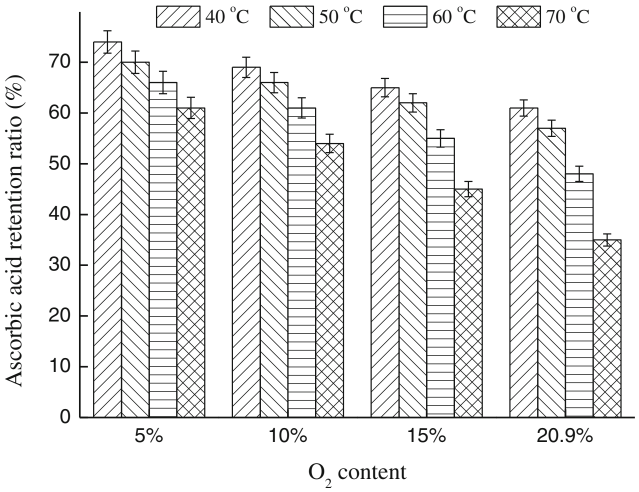

Fig. 7 Ascorbic acid retention ratio of dried carrot at different drying temperatures and O_2 contents

acid content was better retained when the O_2 content was low, which reduced the oxidative reaction of ascorbic acid. Hawlader et al. (2006c) reported that more vitamin C could be retained in final products when drying with inert gas instead of normal air. Ascorbic acid retention ratio decreased obviously with the increase of drying temperature because of the instability of ascorbic acid at high temperature (Goula and Adamopoulos 2006). However, ascorbic acid retention ratio ranged between 74 and 61 % at drying temperatures of 40 to 70 °C when O_2 content was 5 % compared with the values of 61 to 35 % when O_2 content was 20.9 %. Modified atmosphere drying with substitution of O_2 by N_2 can therefore prevent the oxidation of ascorbic acid effectively even at high drying temperatures.

Color

The influences of drying temperature and O_2 content on the Lab and Δ*E* values of the dried products in the modified atmosphere drying of carrot are shown in Table 1 and Fig. 8, respectively. Color is considered as a key quality attribute, and food discoloration is the consequence of various reactions (Krokida et al. 1998). The drying temperature and O_2 content levels in drying atmosphere are important factors to achieve best quality in terms of color (O'Neill et al. 1998). The samples dried with lower temperature and O_2 content had higher *L**, *a**, and *b** values and less Δ*E* values. Hence, the decrease in drying temperature and O_2 content has positive effects on protecting the product appearance. Δ*E* values in the modified atmosphere drying of carrot with 5 % O_2 content ranged from 1.61 to 3.62. Δ*E* values with O_2 contents of 5 and 10 % are obviously lower than those with O_2 contents of 15 and 20.9 %. Therefore, low O_2 content could affect the product color positively and restrain the browning reaction effectively. Product color could be improved with less browning when drying in inert gas (O'Neill et al. 1998; Hawlader et al. 2006a, 2006b).

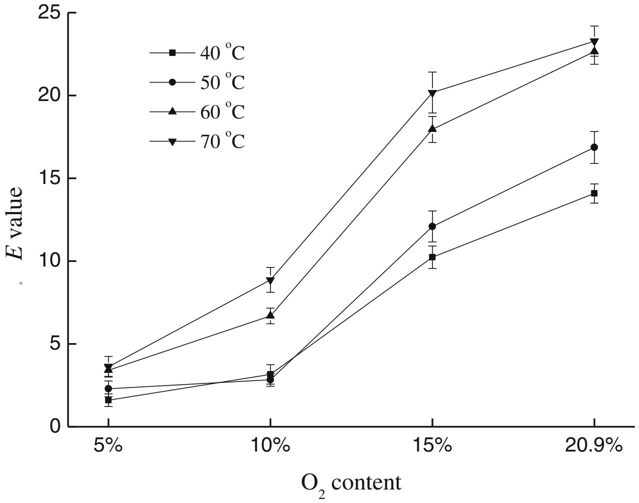

Fig. 8 Color difference of dried carrot at different drying temperatures and O_2 contents

Comparing Figs. 6 and 8, carotenoid content and Δ*E* values had reverse changing trends in the modified atmosphere drying of carrot, that is, Δ*E* value increased but carotenoid content decreased with increasing drying temperature and O_2 content. Carotenoid is a major pigment inside the carrot (Wang and Xi 2005); the loss of color, especially red, is caused by the oxidation and degradation of carotenoid (Singh et al. 2013). The correlation coefficients of carotenoid content for *L**, *a**,

Table 1 Lab values of the carrot products by the modified atmosphere drying

Drying temperature, °C	O_2 content, %	*L**	*a**	*b**
40	5	66.188±1.208	33.560±1.431	32.250±0.400
40	10	64.182±0.707	31.596±1.309	32.026±1.138
40	15	62.924±1.259	27.478±1.464	26.044±1.301
40	20.9	60.144±2.038	25.844±0.841	23.484±1.781
50	5	66.068±0.719	31.706±0.360	32.178±0.594
50	10	64.492±0.790	31.025±0.617	34.236±0.839
50	15	61.778±0.636	26.288±0.588	24.988±1.023
50	20.9	58.900±0.575	21.918±0.398	23.704±0.263
60	5	63.240±1.947	34.420±0.708	32.430±1.466
60	10	61.812±1.386	30.064±0.458	29.886±0.403
60	15	55.800±0.733	22.054±0.982	24.398±0.746
60	20.9	51.140±0.779	21.294±0.307	21.828±0.638
70	5	63.011±1.589	32.431±0.918	32.215±1.482
70	10	59.645±1.693	28.589±0.876	30.032±1.036
70	15	52.468±1.480	22.003±0.932	24.198±1.201
70	20.9	50.001±0.816	20.937±0.518	22.475±0.683

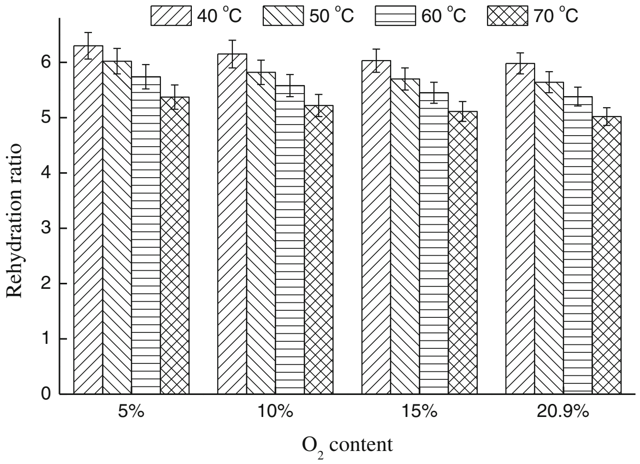

Fig. 9 Rehydration ratio of dried carrot at different drying temperatures and O_2 contents

b^*, and ΔE values were 0.8547, 0.8138, 0.6883, and −0.8253, respectively. Carotenoid content thus strongly correlates with color parameters. Therefore, the modified atmosphere drying with low O_2 content by introducing inert gas, such as N_2, can protect the carotenoid compound of carrot and positively affect the carrot appearance as well.

Rehydration Ratio

The rehydration ratio values of the carrot subjected to modified atmosphere drying at different drying temperatures and O_2 contents are shown in Fig. 9. The rehydration ratio decreased with the increase in drying temperature. Product shrinkage in food drying always happens because food polymers collapse under gravitational force and inner stress during moisture removal (Pan et al. 2007). Given soft tissues and structures inside the carrot, the shrinking occurs easily and continually during carrot drying. Higher drying temperature increases heat transfer rate, accelerates water diffusion and evaporation, and produces higher drying rate and greater shrinkage (Supmoon and Noomhorm 2013). The shrinkage increase could lessen the pores inside samples and cause more compact tissue structure (O'Neill et al. 1998). Hence, the increased loss of porosity and the collapse of cellular structure at high drying temperature may be the main reasons of the decline of rehydration ability in this study.

In Fig. 9, the reduction of O_2 content in the drying atmosphere resulted in a slight increase of rehydration ratio. Different O_2 contents produce different drying rate, as mentioned above, lead to different porosities, and cause various rehydration capacity. Hawlader et al. (2006a) reported that the structures of apple dried with inert gas and normal air differ. Moreover, the existence of O_2 during drying influences the physical property of the sample surface and may transform some open pores into close pores during water removal and sample shrinking. However, the influence of O_2 content on rehydration ratio is not as obvious as that of drying temperature.

Table 2 ANOVA for the overall effects of drying temperature and O_2 content on carotenoid content, ascorbic acid retention ratio, color difference, and rehydration ratio

	Source	Sum of squares	DOF	Mean square	*F* value	*p* value
CC	Drying temperature, X_1	171.6875[a]	3	57.2292	41	<0.001
	O_2 content, X_2	426.1875[a]	3	142.0625	101.776	<0.001
	Error	12.5625	9	1.3958		
	Total variation	610.4375	15			
AARR	Drying temperature, X_1	0.079[a]	3	0.0263	35.349	0.002
	O_2 content, X_2	0.068[a]	3	0.0227	30.428	0.004
	Error	0.0067	9	0.0007		
	Total variation	0.1537	15			
ΔE	Drying temperature, X_1	124.8149[a]	3	41.605	12.47	0.002
	O_2 content, X_2	735.039[a]	3	245.013	73.439	<0.001
	Error	30.0265	9	3.3363		
	Total variation	889.8804	15			
RR	Drying temperature, X_1	1.8825[a]	3	0.6275	3042.379	<0.001
	O_2 content, X_2	0.2868[a]	3	0.0956	463.546	0.004
	Error	0.0019	9	0.0002		
	Total variation	2.1711	15			

F value means Fisher statistical test value of homogeneity test of variance. $F_{0.01}(3,9)=6.99$

CC carotenoid content, *AARR* ascorbic acid retention ratio, ΔE color difference, *RR* rehydration ratio, *DOF* degree of freedom

[a] Indicates extremely significant

ANOVA Results

ANOVA results with Duncan's new multiple range method in modified atmosphere drying are presented in Table 2. All p values are lower than 0.01 and all F values are higher than $F_{0.01}(3,9)=6.99$. Thus, drying temperature and O_2 content have extremely significant effects on carotenoid content, ascorbic acid retention ratio, ΔE value, and rehydration ratio.

Conclusions

A modified atmosphere dryer with a heat pump system and an air recirculation drying system is developed and applied to carrot drying in this study. The inert gas of N_2 is flushed into the dryer to achieve hot-air drying with different O_2 contents. Drying temperature has significant effects on drying time and D_{eff} value. The decrease in O_2 content has slightly positive effects on drying time and D_{eff} value. The drying temperature and O_2 content have significant effects on the quality parameters of carrot products, such as carotenoid content, ascorbic acid retention ratio, ΔE value, and rehydration ratio. The decrease in drying temperature and O_2 content could result in higher carotenoid and ascorbic acid retention, protect product appearance, and improve rehydration ability. The reduction of O_2 content in drying air could reduce the contact possibility between O_2 and samples, restrain the oxidization and degradation of carotenoid and ascorbic acid effectively, and improve rehydration ability and color protection. Good quality parameters, including carotenoid content, ascorbic acid retention ratio, ΔE value, and rehydration ratio, are achieved at drying temperatures of 40 to 70 °C when O_2 content is 5 %. Therefore, the modified atmosphere drying is an effective and promising method for enhancing carrot quality and achieving a satisfied drying result.

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