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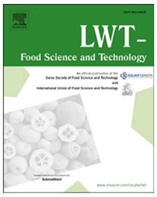

Pulsed vacuum drying of rhizoma dioscoreae slices

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ABSTRACT

This research explored the application of pulsed vacuum technology on drying of rhizoma dioscoreae slices. Influences of thickness, temperature and pulsing ratio on drying characteristics and rhizoma dioscoreae quality (color, rehydration characteristics and microstructure) were analyzed. Increasing temperature and decreasing thickness resulted in higher drying rate. Pulsing ratio was adjusted according to relationships between material temperature and chamber pressure, as well as drying rate which agreed well with Weibull model. The optimized condition, that product temperature increased during atmospheric pressure period and then decreased because of moisture evaporation through the whole vacuum period, was obtained according to rhizoma dioscoreae temperature-time curve with highest drying rate and best retention of product quality. The amount of pressure drops was found to be more influential than material temperature in accelerating drying rate. Prolonged vacuum duration was helpful in inhibiting browning of rhizoma dioscoreae slices, forming puffed structure and accordingly obtaining better rehydration characteristics.

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1. Introduction

Rhizoma dioscoreae, the genus *Dioscorea*, is a popular vegetable in countries of Africa, Oceania and Southeast Asia (Myoda et al., 2006). Rhizoma dioscoreae consists mainly of starch and some proteins, lipids and vitamins, with higher average crude protein content than other root vegetables (Xiao et al., 2012). It has been widely used as one of the traditional Chinese herbal medicinal materials to promote human health (Hsu,Chen, Weng & Tseng, 2003), also as functional foods in daily life (Bhandari & Kawabata, 2004). The annual market demand of rhizome dioscoreae in China amounts to one million tons domestically and above 1.5 million tons internationally, respectively (Chen, Chen, Wu, Chen & Lu, 2008). Fresh rhizoma dioscoreae is apt to get rotted due to its high moisture content, therefore, it is usually dried to minimize microbial spoilage (Tian, Zhao, Huang, Zeng & Zheng, 2016) and to extend shelf-life (DePaz & Dale, 2002) before long-term preservation, especially for medicinal use. Due to the existence of polyphenol oxidase (PPO), peroxidase (POD) and other enzymes, browning is a big problem during rhizoma dioscoreae drying which will cause quality deterioration of dried products (Graham-Acquaah, Ayernor, Bediako-Amoa, Saalia & Afoakwa, 2014).

In order to prevent enzymatic browning, rhizoma dioscoreae is usually vacuum dried (Arévalo-Pinedo & Murr, 2006). Color and nutrition of materials have been proved to be better reserved by vacuum drying (Jaya & Das, 2003; Uribe & Marin, 2016). However, the cost is pretty high to hold vacuum condition during the whole drying process. What's more, when the drying condition is kept at vacuum for long time, an equilibrium state of water vapor partial pressure inside and outside the material is easily obtained resulting in a low drying rate (Chua & Chou, 2004; Gao, Wu & Zhang, 2010; Hsu et al., 2003; Maache-Rezzoug, Rezzoug & Allaf, 2001).

Pulsed vacuum drying, also called dehydration by cyclical or successive pressure drop (DDS), is a good solution to maximize energy efficiency while retaining product quality compared with continuous vacuum drying (Haddad, Juhel, Louka & Allaf, 2004; Sanya, Rezzoug & Allaf, 2003). Pulsed vacuum drying could lead to an obvious improvement in drying rate or food quality, such as better rheological properties of scleroglucan as compared with continuous vacuum drying (Maache-Rezzoug et al., 2001), better reserved color of bio-product and fish as compared with hot air drying or vacuum freeze drying (Chua, Chou, Mujumdar, Ho & Hon, 2004; Haddad et al., 2004), less shrinkage of waterlogged and fresh wood (Sanya et al., 2003) and lower cleavage ratio of paddy rice (Cong, Haddad, Rezzoug, Lefevre & Allaf, 2008) as compared with controlled instantaneous pressure drop (also called DIC) (Haddad et al., 2004).

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Nomenclature

DR	drying rate, g/(g × h)
M_t	moisture content on dry basis at time t, g/g
t	drying time, min
W_t	weight at time t, g
W_{ds}	weight of absolute dry soild, g
MR	moisture ratio
M_0	initial moisture content on dry basis, g/g
α	scale parameter, s
β	shape parameter
G	lag factor
S	drying coefficient
Bi	Biot number
$D_{eff,F}$	effective moisture diffusivity calculated by Fick's second law, m^2/s
r_e	volume equivalent radius, m
k_1	the slope of linear regression curve of time and lnMR
$D_{cal,W}$	estimated effective moisture diffusivity calculated by Weibull model, m^2/s
R_g	physical dimension parameter
$D_{eff,D}$	effective moisture diffusivity calculated by Dincer model, m^2/s
L	the thickness of rhizoma dioscoreae slices, m
k	mass transfer coefficient, m/s
t_1	vacuum duration, min
t_2	atmospheric pressure duration, min
RC	rehydration coefficient
T	temperature, °C
P	pressure, kPa
W_r	weight after rehydration, g
W_d	weight after pulsed vacuum drying, g
W_0	initial weight, g
R^2	coefficient of determination
$MR_{exp,i}$	experimental dimensionless moisture ratio
$MR_{pre,i}$	predicted dimensionless moisture ratio
N	number of data

Experimental results by former researchers showed that vacuum duration and atmospheric pressure duration, as well as their ratio, namely pulsing ratio, were the key factors influencing pulsed vacuum drying rate (Cao, Gao & Lin, 2009; Gao et al., 2010; Yang, Jia, Wu, Wu & Jin, 2015). Specifically, the number of pressure drops was found to have a positive effect on the drying rates according to observations of bio-products and black tea (Chua & Chou, 2004; Gao, Dong & Ye, 2016). A shorter vacuum duration, corresponding to more cycles under the same atmospheric pressure duration, led to shorter drying time during pulsed vacuum drying based on the study of Baker's yeast (Rakotozafy, Louka, Thérisod, Thérisod & Allaf, 2000). Contrary to this, the optimized vacuum durations of both carrots and lotus pollen were proved not to be the shortest one with an invariable atmospheric pressure time (Cao et al., 2009; Fang, Zhang, Wang & Zhang, 2016). Conclusions of former researches are inconsistent concerning determination of optimum pulsing ratio, partly because most scholars usually obtained the optimized pulsing ratio by try and error, which is not enough to reveal the principle of pulsed vacuum drying technology. Therefore, further study on relationship between pulsed vacuum drying parameters and material mass transfer was in great need.

According to our preliminary experiments, material temperature increased during atmospheric pressure period and rapidly dropped with pressure drop to vacuum condition, suggesting there might be certain connection among pressure, material temperature and pulsing ratio. This might be a breakthrough point to be able to theoretically determine the optimal drying parameters.

Weibull distribution function, which has been widely applied in materials science, pharmacology and thermodynamics, was also used to describe drying process (Bai et al., 2013) using scale parameter α, the time to remove 63% of initial moisture, and shape parameter β, which has something to do with the mass transfer rate at the beginning stage. Dincer model, which could predict the moisture curve with the relationship between Biot number and lag factor, was also used to analyze the drying process based on lag factor and drying coefficient (Dincer, Hussain, Yilbas & Sahin, 2002).

The objectives of this study were to: (1) study relationships between drying performance and cyclic pressure and material temperature changes, (2) investigate the effects of thickness, temperature and pulsing ratio on drying characteristics, so as to establish the optimal drying condition based on drying rate and rhizoma dioscoreae quality, (3) analyze pulsed vacuum drying process of rhizoma dioscoreae using Weibull model and Dincer model, so as to discover the moisture diffusion and mass transfer rule. Rhizoma dioscoreae.

2. Materials and methods

2.1. Material

Rhizoma dioscoreae of the same variety were purchased from a local market in Beijing, China and stored in a cool dry place for less than one week before experiment. The initial moisture content of the sample was 79.56% on wet basis, determined by a vacuum drying oven (D27-6050, Jinghong Instrument Co., Ltd., Shanghai, China) at 70 °C (AOAC, 1995). Due to the protection of the peel, the moisture content of the sample kept constant during the one-week storage according to our preliminary experiment.

Rhizoma dioscoreae tubers were peeled, washed with distilled water, and cut into round slices at three different thicknesses (3, 5 and 7 mm). The slime on the surface was then washed away and the extra surface water was wiped off using blotting paper.

2.2. Pulsed vacuum dryer

The drying experiments were carried out using a custom-built laboratory pulsed vacuum dryer as shown in Fig. 1, the cube-shaped drying chamber of which having a capacity of 0.216 m^3. The dryer is consisted mainly of heating, control and vacuum systems.

After the vacuum pump was turned on, the pressure in drying chamber turned from atmospheric pressure to vacuum, kept on vacuum condition for the whole vacuum holding period, the solenoid valve was then activated to break the vacuum state and the pressure in chamber turned back to and kept at atmospheric pressure till the end of atmospheric pressure duration. The pressure in the drying chamber alternated between vacuum and atmospheric pressure cyclically and continuously until the end of drying period. A condenser was used to condense water vapor in drying chamber so that it would not condense back to the surface of materials.

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