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Effective moisture diffusivity of pomegranate arils under going microwave-vacuum drying

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ABSTRACT

Drying of pomegranate arils was done using microwave-vacuum technique, using microwave power of 25 to 95 W, vacuum pressure of 25 to 195 mm Hg and sample mass of 65 to 235 g. The effective moisture diffusivity varied from 5.18×10^{-11} to 6.58×10^{-10} m^2/s. Effective moisture diffusivity (D_{eff}) values were found to increase as microwave power increases or sample mass decreases for constant values of remaining variables while vacuum pressure had negligible effect. A third order polynomial relationship was found to correlate the effective moisture diffusivity (D_{eff}) with moisture content. Multivariate polynomial models were also developed for estimating the effective moisture diffusivity as a function of the microwave-vacuum drying process parameters.

1. Introduction

Microwave-vacuum drying has several advantages over conventional drying, such as higher drying rate, minimal heating at locations with less water thus reducing overheating of locations where heating is not required. However, for microwave-vacuum drying to be more useful at the industrial level, it needs information on moisture diffusion models that could describe the process accurately. The diffusion coefficient of a food is material property and its value depends upon the conditions within the material. Effective moisture diffusivity describes all possible mechanisms of moisture movement within the foods, such as liquid diffusion, vapor diffusion, surface diffusion, capillary flow and hydrodynamic flow but exact mechanism is still to be studied (Kim and Bhowmik, 1995).

A knowledge of effective moisture diffusivity is necessary for designing and modeling mass-transfer processes such as dehydration, adsorption and desorption of moisture during storage. In literature, various methods are available to determine the effective moisture diffusivity. Among those, Regular Regime approach is quite commonly used to determine moisture dependent diffusivity in many foods, especially those having sugars. In this approach, influence of initial drying condition on the drying process is negligible and the concentration at the center of the drying sample changes with time. Several researchers used this approach to determine the concentration dependent effective diffusivity from desorption (time–weight change) curves are being briefly discussed here. Schoeber's (1976) method involves the determination of desorption rate v/s average moisture content, Sherwood number and numerical differentiation in regular regime which make it very difficult to determine diffusion coefficient from the scattered experimental data. Couman's (1987) method assumes the power law dependence of effective diffusivity. Couman's method is a simplified version of Schoeber's but the proposition of a constant power law index does not represent the real cases. Yamamoto et al. (1997) recognizes that the power law index is a function of moisture content.

A widely accepted mechanism of moisture loss during drying of granular material is liquid and/or vapor diffusion. The only diffusion-based thin layer drying equation that explicitly relates the diffusion coefficient to drying rates is the analytical solution of Fick's equation. The most popular form used in describing thin layer drying is the series solution, depends on the initial and boundary condition considered and shape of the material. Fickian diffusion model has been found to give accurate descriptions of the thin layer drying characteristics of white beans (Adu and Otten, 1996) and parboiled wheat (Mohapatra and Rao, 2005).

Several studies have been carried out to determine the effective moisture diffusivity and investigated its dependence with geometry, moisture content and temperature of agricultural products such as potato (McMinn et al., 2003), garlic cloves (Sharma and Prasad, 2004) and mint leaves (Ozbek and Dadali,2007). The heating mechanism and conditions within a material during microwave-vacuum drying are different from those during

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Nomenclature

a, b ,c	dimension of pomegranate arils	P	vacuum pressure (mm Hg)
A, B, C, D	regression coefficient of empirical model	p	probability level
ANOVA	analysis of variance	Q	microwave power
C.V.	coefficient of variance	r	radius of cylindrical aril (m)
D_{eff}	effective moisture diffusivity	R^2	coefficient of determination
F_0	Fourier's number	RSM	response surface methodology
M	moisture content (g water/g dry matter)	S.E.	standard error
M_{avg}	average moisture content (g water/g dry matter)	t	drying time (min)
M_{e}	equilibrium moisture content (g water/g dry matter)	λ_1	first root of the bessel function of zero order
MR	moisture ratio	λ_{n}	roots of Bessel's function of zero order
M_{t}	moisture content at time t, g water/g dry matter		
MVD	microwave vacuum drying		

conventional drying. No information is available in literature on diffusion characteristics for microwave-vacuum drying of pomegranate arils yet. The objective of this study has, therefore, been to determine the effective moisture diffusivity of pomegranate arils during a microwave-vacuum drying process and its dependence on factors such as microwave power, vacuum pressure and sample mass that essentially influence drying rates.

2. Materials and methods

Fresh pomegranates (*Punica granatum L.*) of "Maridula" variety were procured from local market of New Delhi and stored at 10 °C in cold storage. Prior to experiments, pomegranates were thoroughly washed with water to remove the dirt and sorted to remove damaged or decayed fruits. The arils were separated manually using a stainless steel knife, giving vertical cut to the fruits. The initial moisture content in arils was found in the range of 354.55 to 455.56% (d.b.) using hot air oven method.

A domestic microwave oven (BPL make, model 800G) having cavity dimension of 490 mm(W) × 322 mm(H) × 373 mm(D) was modified and developed into microwave vacuum drier. The oven had a magnetron of 800 W operating at 2450 MHz and 6 power levels. The power of magnetron was varied by changing its anode current as described by Tong et al., 1993. A high voltage transformer was incorporated in the circuit to supply current to the anode of the magnetron separately. A 270 V (AC)/15 A variac was also placed on the primary side of the high voltage transformer, to vary the anode current, thus varying the output power of the magnetron between 0 and 800 W. The output power of magnetron was measured by calorimetric method (Tulsidas, 1994). A container made of polycarbonate with provision to spread pomegranate arils sample over glass plate was placed inside the microwave oven cavity. A vacuum pump with pressure regulating valve was connected to the container for maintaining the desired level of vacuum pressure inside it. The extent of vacuum in the container was monitored with a vacuum gauge. An airtight condenser was used in the vacuum line for condensing the water vapor released from the samples during drying. Microwave-vacuum drying experiments for pomegranate arils were conducted without imparting any pretreatment according to a second order central composite rotatable design (CCRD) in the range of microwave power (25 and 95 W), vacuum pressure (25 and 195 mm Hg) and sample mass (65 and 235 g).

Sample of pomegranate arils was uniformly spread in single layer (<10 mm thickness) over glass plate inside the vacuum container and after attaining the required vacuum, appropriate level of microwave power was applied. The weight of the sample was recorded at every 5 min interval after switching off the microwave oven and releasing the vacuum, which took about 30 to 60 s for each observation. The samples were dried until its moisture content was reduced to 5 to 6% (d.b.).

2.1. Theoretical approach

The method of slopes was used in the estimation of effective moisture diffusivity of pomegranate arils at corresponding moisture contents under different drying conditions. The exact size of fresh pomegranate aril is a solid cone (sphericity <0.8). But no formula is available in literature for prediction of moisture diffusivity for cone shaped geometries. During microwave vacuum drying of pomegranate arils greater shrinkage (approx. 50%) is observed and dried arils seems like a cylinder. Hence they were assumed as an infinite cylinder (i.e. moisture diffusion occurring radially outwards only) by considering approximately $a = b \neq c$ for fresh arils where a, b, c are the dimension of cylinder (Sharma and Prasad, 2004).

Following assumptions were made for the infinite cylindrical shaped body of the pomegranate arils (Crank, 1975).

1. Moisture is initially uniformly distributed throughout the mass of a sample.
2. Mass transfer is symmetric with respect to centre of the cylinder.
3. Resistance to the mass transfer at the surface is negligible compared to internal resistance to sample.
4. Diffusion coefficient is constant.

The following solution to the Fickian equation was, therefore, used

$$\frac{M_t - M_e}{M_o - M_e} = \sum_{n=1}^{\infty} \frac{4}{\lambda_n^2} \exp\left(-\frac{\lambda_n^2 D t}{r^2}\right) \quad (1)$$

Where, λ_n are the roots (2.405, 5.52, 8.654……..) of Bessel function of zero order $J_0(r) = 0$. For long drying times and $n > 1$, only the first term in Eq. (1) is significant (Lopez et al., 2000) and the Eq.(1) becomes

$$\mathrm{MR} = \frac{M_t - M_e}{M_o - M_e} = \frac{4}{\lambda_n^2} \exp\left(-\frac{\lambda_1^2 D t}{r^2}\right) \quad (2)$$

The equilibrium moisture content during microwave vacuum drying was considered zero, due to vacuum condition of process (Kiranoudis et al., 1997). Eq.(2) is evaluated numerically for Fourier number, $F_o = \mathrm{D}t/r^2$, for diffusion and thus can be rewritten as:

$$\mathrm{MR} = \frac{4}{\lambda_n^2} \exp\left(-\frac{\lambda_1^2 \mathrm{D}t}{r^2}\right)$$