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Moisture desorption isotherm, diffusivity and finite element simulation of drying of macadamia nut (*Macadamia integrifolia*)

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ABSTRACT

This paper presents moisture diffusivity, equilibrium desorption isotherm and finite element simulated drying of macadamia nut. In order to create the desorption isotherm, the equilibrium moisture content was determined by using the gravimetric method. The Modified Oswin model fitted the best experimental data and is satisfactory for the prediction of the moisture desorption isotherm of macadamia nuts. The thin layer drying experiments of the kernel and shell of the macadamia nuts were conducted at a temperature of 40 °C, 50 °C and 60 °C and relative humidity of 10%, 20% and 30%. The moisture diffusivity of the kernel and shell of the macadamia nut was determined by minimizing the sum of square of the deviation between the predicted and the experimental moisture contents values during the thin layer experiments. The diffusivity of the kernel and shell was expressed as functions of temperature using the Arrhenius type equation and the moisture diffusivity of the kernel was higher than that of the shell of the macadamia nuts. A two-dimensional finite element drying model of macadamia nut was developed and this model predicted reasonably the moisture contents during drying. The model can be used to reveal spatial and temporal changes in moisture content inside the macadamia nut.

1. Introduction

The macadamia (*Macadamia integrifolia*) is a native of the rainforests of eastern Australia (Storey and Hamilton, 1954) and it is now grown in other parts of the world. It was introduced to the upland areas of Thailand more than 40 years ago. In Thailand, the macadamia plantation areas of macadamia are mainly located in northern and northeastern parts of the country and the annual production is 6500 tons which has a market value of 14 million US dollars. Macadamia nuts are rich in monosaturated fatty acids and are delicious. Although the productions of macadamia nuts are limited in Thailand, it has high demands and the price of the nuts is also high.

Fresh macadamia nuts have high moisture content at the harvest and are prone to deterioration. High moisture content leads to fungal growth, reduction in shelf life, and increase in germination. Hence the moisture needs to be removed as quickly as possible to avoid deterioration and maintain the quality. After harvesting, macadamia nuts need to be dried. To dry macadamia nuts efficiently and maintain the quality, it is necessary to know their drying characteristics in order to optimize the drying operations and to obtain optimal design of macadamia nut dryers. Knowledge of the transport processes is essential for production of quality dried product and energy conservation. Understanding and controlling the drying processes are also important in establishing improved design guidelines for drying systems. This requires an

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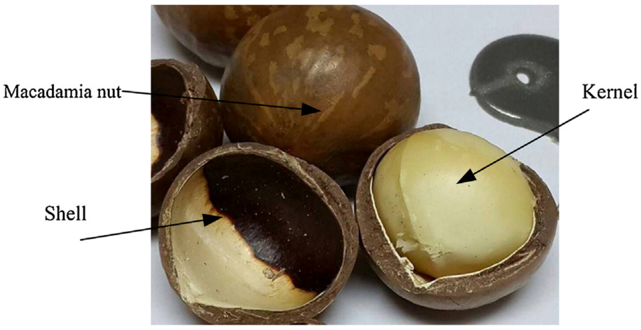

Fig. 1 – Macadamia nut comprising of kernel and shell.

accurate description of the drying mechanism (Haghighi and Segerlind, 1988).

Macadamia nut consists of kernel and shell which have different diffusivities and finite element is the most appropriate technique to model the drying characteristics of a product whose components have different diffusivities and irregular shapes. The macadamia nut, kernel and shell used in this study are shown in Fig. 1. This finite element technique can be used to model the macadamia nuts for accurate prediction of their drying characteristics, and optimum design and operation of macadamia nut dryer require such a model. Also in order to properly understand transfer processes during drying for production of quality dried macadamia nuts using the finite element simulation, knowledge of diffusivity and moisture sorption of the macadamia nuts is essentially needed.

Several studies have been reported on moisture diffusivities of fruits (Babalis and Belessiotis, 2004; Janjai et al., 2008a, b, 2010). No study has been reported on the diffusivities of the different components of macadamia nuts and there exists a research gap on diffusivity of macadamia nut. Many studies have been reported on equilibrium moisture content models (Palipane and Driscoll, 1992; Lomauro et al., 1985; Mir and Nath, 1995; Lahsasni et al., 2004; Kaymak-Ertekin and Gedik, 2004). Palipane and Driscoll (1992) fitted four sorption models to the experimental data of in-shell macadamia nuts and GAB model with six constants where the monolayer moisture content varied with temperature according to an Arrhenius-type equation gave the best fit for both adsorption and desorption data. Only limited study has been conducted on equilibrium moisture contents of macadamia nuts and needs a comprehensive evaluation of equilibrium moisture contents of macadamia nuts.

Many studies have been reported on drying of fruits and nuts (Abalone et al., 2006; Babalis and Belessiotis, 2004; Goyal et al., 2006; Hii et al., 2009; Kashaninejad et al., 2006; Menges and Ertekin, 2006; Sacilik and Elicin, 2006). A number of studies have been conducted on finite element modeling of drying of fruits. Janjai et al. (2008a, b, 2010) reported finite element drying of mango slices, longan and litchi fruits and Nilnont et al. (2012) reported finite element simulation of coffee drying. The prediction of finite element model of drying of longan, litchi and coffee using different diffusivities are excellent.

Several studies have been reported on drying of macadamia nuts (Borompichaichartkul et al., 2009; Janjai et al., 2014; Silva et al., 2006; Wall and Gentry, 2007; Palipane and Driscoll, 1994) and no study has been reported on finite element simulation of drying of macadamia nut. There exists a research gap and literature gap on modeling of finite element drying of macadamia nut which consider the different diffusivities of the kernel and shell. Therefore, this work aims to develop a finite element simulation of drying of macadamia nut considering the composite structure of kernel and shell of the macadamia nut. To provide the diffusivities of the different components of the macadamia nut for the finite element model, the moisture diffusivities of the different components of macadamia nut were experimentally determined under controlled conditions of temperature and relative humidity using a laboratory dryer. Further study was also conducted to determine equilibrium moisture content experimentally and to find a simple but realistic model for equilibrium moisture content of macadamia nut.

2. Materials and methods

2.1. Experimental study

The macadamia nuts used in this experiment were collected from Loei province in northeastern Thailand. The initial moisture content was about 35–37% (db) and the average diameter of the macadamia nuts was 2.8 cm. Thin layer drying was conducted for in-shell macadamia nuts, kernels and shells to determine drying characteristics and diffusivities under controlled conditions of temperature and relative humidity. The in-shell macadamia nuts, kernels and shells were dried at the temperature of 40 °C, 50 °C and 60 °C, the relative humidity of 10%, 20% and 30% and the air velocity of $1\,\mathrm{m\,s^{-1}}$. Schematic diagram and pictorial view of the laboratory dryer used to determine the diffusivities and drying characteristics are shown in Fig. 2. The laboratory dryer consists of a ceramic packed bed for producing saturated air at a particular temperature, an electrical heater, a blower, a drying section, measuring sensors, recording device and a controlling system. In this laboratory dryer, the blower forces ambient air through a humid ceramic packed bed. The air absorbs moisture while it passes through the packed bed. At the top of the packed bed, this air leaves in a saturated condition and this saturated air is heated by the air heater. There are two options: (a) through-flow drying and (b) over-flow drying. In this work, over-flow drying was used. With this option, air passes across the product placed on the tray for over-flow drying (see Fig. 2(a)). The relative humidity (rh) and temperature of the drying air are controlled by adjusting the power supply to the air heater and the water heater using a psychometric chart as a guideline.

Before starting the experiment, the laboratory dryer is allowed to run for about 30 min to reach a steady temperature. For each experiment of drying of in-shell macadamia nuts, kernels or shells about 130 g of the product was placed in the drying tray. The shells were cut into rectangular slabs and used for the experiments. The drying air temperature was monitored using thermocouples (K type, accuracy ±2%) and these thermocouples were connected to a digital data logger (Yokogawa, Model DC100). Voltage from the thermocouples was converted into temperature. The weights of macadamia nuts were monitored by a load cell (accuracy ±1%). Electrical signal from the load cell was passed into a data logger (Wisco, Model ML21) and the signal was converted into weight. The readings were taken every hour and about 35 h of drying time were required for the product to reach the final moisture content of about 8% (db). The thin-layer drying tests were conducted in the temperature range of 40–60 °C and the relative humidity of the drying air in the range of 10–30%. For each case namely, in-shell-nuts, kernels and shells, nine sets of experiments were conducted.

2.2. Diffusivities of components of macadamia nuts

Fick's second law of the unsteady state diffusion, neglecting the effects of temperature and total pressure gradient, can be used to describe the drying behavior of the kernel and shell (Bala, 1997). It can be written as:

$$\frac{\partial M}{\partial t} = \nabla \cdot (D \nabla M) \tag{1}$$

where M is moisture content, D is diffusivity and t is time.