Applied Thermal Engineering 29 (2009) 2849–2854

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Models of fluidized bed drying for thin-layer chopped coconut

T. Madhiyanon [a,*], A. Phila [a], S. Soponronnarit [b]

[a] Department of Mechanical Engineering, Mahanakorn University of Technology, Bangkok 10530, Thailand
[b] School of Energy, Environment and Materials, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand

ARTICLE INFO

Article history:
Received 7 July 2008
Accepted 7 February 2009
Available online 14 February 2009

Keywords:
Activation energy
Coconut
Effective diffusivity
Fluidized bed
Thin-layer

ABSTRACT

Methods for efficiently drying agricultural products are in ever-increasing demand. Due to its thorough mixing ability, a fluidized bed technique was employed to evaluate the drying kinetics of thin-layer chopped coconut. The experiments were conducted at drying temperatures of 60–120 °C and a constant velocity of 2.5 m/s. Chopped coconut was dried from about 105% d.b. to approximately 3% d.b. The moisture transport phenomenon in fluidized bed thin-layer drying is described by immense acceleration in MR diminution in the early stage of drying, followed by considerable deceleration. Falling-rate drying, an outgrowth of restraining moisture transfer via internal mass-diffusion mechanism, thoroughly characterized chopped coconut drying. Among the 10 selected models, statistic analysis inferred that the Modified Henderson and Pabis model could predict changes in moisture content most accurately. Compared with the values of D_{eff} derived from Fick's law for other food and biological materials usually dried in conventional tray dryers, the current values (5.9902×10^{-8}–2.6616×10^{-7} m^2/s) were substantially high, principally attributable to the unique characteristic of fluidized bed drying, remarkably encouraging heat and mass transfer. Activation energy was also described.

1. Introduction

Coconuts are a widely cultivated economic crop in many parts of the world. Thailand, one of the world's 10 largest producers, generates about 1.5 million tons of coconut annually [1]. This product is consumed in various types of coconut-derived products – coconut milk, coconut flour, coconut juice, and desiccated coconut (DCN). The fine desiccated coconut, with moisture content of around 3% d.b. [2], is typically applicable to decoration ice cream, cake and donuts, and as the principal flavoring ingredient in chocolate bars.

Many studies have emphasized drying kinetics and thin-layer drying models for fruits, vegetables, and the by-products of some industrial processes – mint leaves [3], olive cake [4], strawberries [5], organic apple slices [6], apple pomace [7], green beans [8], parboiled wheat [9], corn [10], carrots [11], rosehip [12], spirulina [13], black tea [14], raw mango slices [15], young coconut [16] and olive oil extraction [17]. As a crucial factor influencing drying kinetics, drying temperature participated intimately in the drying-rate constants (k) of the drying models. In consequence, several studies ascertained a variety drying-rate constants, each for a specific temperature [3–5,8,10,11], while others attempted to relate drying-rate constants to drying temperature [6,7,9,12,16,17].

Although satisfactory for a variety of biological materials, the preceding thin-layer models provided no data for chopped coconut, and most originated from tray dryers, traditionally employed to dehydrate assorted materials. Consequently, some drawbacks are inherent in their use with an extended drying period and inconsistent properties of the products to be dried. Renowned as the most efficient drying technology because of its characteristic thorough mixing, which fosters vigorous heat and mass transfer, the potential of the fluidized bed has become increasingly recognized for drying food products [2,18]. The thin-layer characteristic, derived from fluidized bed drying is distinguished from conventional convective drying by the mixing motion, which enhances heat/mass transfer.

In this study, therefore, the attention is attracted to the thin-layer drying kinetics of finely chopped coconut in a fluidized bed dryer, and to fit various thin-layer models in which the drying-rate constants and model coefficients rely on drying temperature. In addition, effective diffusivity and activation energy are described.

2. Material and methods

2.1. Materials

Mature coconut with husk peeled off was cracked and washed thoroughly to remove dust and other foreign materials, and then soaked in 50-ppm chlorine solution for 5 min to inactive microorganisms [2]. It was chopped finely using a mechanical chopper to

* Corresponding author. Tel.: +66 (0) 2988 3666x3107; fax: +66 (0) 2988 3655x3106.
E-mail addresses: thanid_m@yahoo.com, thanid@mut.ac.th (T. Madhiyanon).

1359-4311/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.applthermaleng.2009.02.003

Nomenclature

a, b, c	essential coefficients of the models	p	number of constants
D_0	pre-exponential factor of the Arrhenius equation (m^2/s)	P	mean relative percent error
D_{eff}	effective diffusivity (m^2/s)	r	radius of the sphere (m)
E_a	activation energy (kJ/mol)	R	universal gas constant (kJ/mol K)
g, h, k, k_0, k_1	drying-rate constants of the models (min^{-1})	R^2	coefficient of determination
M	moisture content (kg water/kg dry matter)	Residuals	sum of residual
$M(t)$	moisture content at any time of drying (kg water/kg dry matter)	RMSE	root mean square error
M_0	initial moisture content (kg water/kg dry matter)	t	drying time (min)
M_{eq}	equilibrium moisture content (kg water/kg dry matter)	T	drying-air temperature (°C)
MR	moisture ratio	T_{abs}	absolute temperature (K)
$MR_{exp,i}$	experimental moisture ratios		
$MR_{pre,i}$	predicted moisture ratios	*Greek letter*	
n	positive integer, essential coefficients of the model	χ^2	reduced chi-square
N	number of observations		

produce uniform coconut pieces. The mean diameter (d_m) obtained from sieving process was found to be 2.28 mm. Initial moisture content was about 105 ± 15% dry basis (d.b).

2.2. Experimental apparatus

Fig. 1 shows a schematic diagram of the overall experiment setup. The fluidized bed dryer consists of an acrylic cylindrical drying chamber with 210 mm i.d., 1200 mm in height. Supply air ducts and a cyclone are made of stainless steel. The fluidizing air was supplied by a 2-hp blower, and a 5 kW electrical heater was employed to heat up the air to desired drying temperatures. The temperatures were monitored using a data logger with an accuracy of ±1 °C and type-K thermocouples, and controlled to ±1 °C by a controller. Air velocity was adjusted manually and measured by a Venturi meter cooperated with a differential pressure sensor (accuracy ± 2%). In the earlier experiments, it was apparent that when fluidizing air penetrated through an air-distributor, portions of the chopped coconut pieces originally distributed thinly were swept aside, resulting in many bare spots on the distributor surface. Then, the upwardly projecting airstream will take shortcuts through these bare spots and the coconut will keep still. To overcome this problem, continuously-rotating blades (stirring blades) operating at 40 rpm were disposed centrally within the drying chamber and just above the air-distributor plate, to stir the chopped coconut; this prevented the aggregation of chopped coconut particles being dehydrated, and reliably spread them uniformly over the distributor surface during the drying process. Observations after the installation of the stirring blades found fluidization had been achieved. Samples were removed at each nominated interval in the drying process and weighed with an electronic balance (accuracy ± 0.0001 g).

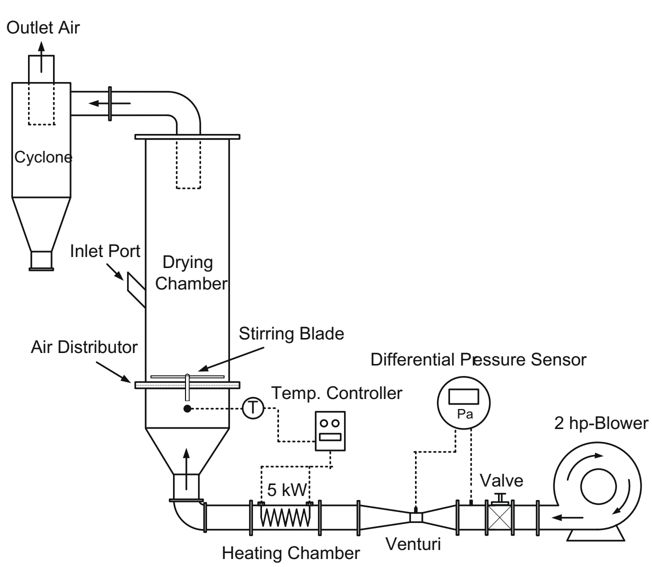

Fig. 1. A schematic diagram of fluidized bed apparatus.

2.3. Experimental procedure

The experiments were performed at drying temperatures varying from 60 to 120 °C, with 10 °C increment, and a fixed fluidizing velocity of 2.5 m/s for all circumstances. Use of a velocity less than 2.5 m/s was unable to encourage fluidization of the chopped coconut, even with concurrent use of stirring blades, while a velocity much greater than 2.5 m/s caused particle elutriation. The dryer operated without product inside for 30 min to stabilize the drying conditions. To determine how the effective diffusion coefficient (D_{eff}) was contingent on drying temperature, 10 ± 0.1 g of minced coconut was layered as thinly as possible on the air-distributor plate, to minimize temperature drop across the layer. Although the layer might not be exactly a single layer, it permitted only about 1 °C drop in drying-air temperature. The product was dried to about 3% d.b. Simultaneously, to trace changes in moisture content during the drying process and to prevent any disturbance of the moisture content evolution during the process due to sampling, the experiment was stopped at the end of each sampling interval, and most of the coconut was collected for determination of moisture content. Thereafter, a subsequent experiment for a succeeding sampling interval started with the same conditions: the same initial amount of product (10 ± 0.1 g), initial moisture content, and temperature. Coconut was gathered periodically: at 10-s intervals for the first 0–2 min, at 20-s intervals for 2–5 min, and then at 1-min intervals for 5–10 min. Most of the coconut withdrawn at each interval was cooled down and packed in low density polyethylene bags sealed by heat, before analyzed for moisture content. To minimize measurement uncertainties, all experiments were replicated at least 2 times, except some (at 60, 80, 110, and 120 °C) which demonstrated noticeable differences between the duplicate and the original, which were further replicated once; the averages of the results were used in analysis. The whole sample (≈10 g) collected at each interval was divided into three smaller amount samples, and these triplicate samples were dried in a convective oven