Journal of the Saudi Society of Agricultural Sciences (2016) **15**, 179–187

King Saud University

Journal of the Saudi Society of Agricultural Sciences

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FULL LENGTH ARTICLE

Energy analyses and drying kinetics of chamomile leaves in microwave-convective dryer

Ali Motevali [a], **Saeid Minaei** [a,*], **Ahmad Banakar** [a], **Barat Ghobadian** [a], **Hosain Darvishi** [b]

[a] *Department of Biosystems Engineering, Faculty of Agriculture, Tarbiat Modares University, Tehran, Iran*
[b] *Department of Biosystems Engineering, Faculty of Agriculture, University of Kurdistan, Sanandaj, Iran*

Received 1 April 2014; revised 30 September 2014; accepted 5 November 2014
Available online 2 December 2014

KEYWORDS

Chamomile;
Drying characteristics;
Energy consumption;
Efficiency;
Microwave-convective drying

Abstract Drying characteristics and energy aspects as well as mathematical modeling of thin layer drying kinetics of chamomile in a microwave-convective dryer are reported in this article. Drying experiments were carried out at 8 microwave power levels (200–900 W), air temperature of 50 °C, and air velocity of 0.5 m/s. Increasing the microwave output power from 200 to 900 W, decreased the drying time from 40 to 10 min. The drying process took place in the falling rate period. The Midilli et al. model showed the best fit to the experimental drying data. Moisture diffusivity values increase with decreasing moisture content down to 1.70 (kg water kg^{-1} dry matter) but decrease with a further decrease in moisture content from 1.72 to 0.96 (kg water kg^{-1} dry matter). The average values of D_{eff} increased with microwave power from 5.46 to 39.63×10^{-8} ($m^2\ s^{-1}$). Energy consumption increased and energy efficiency decreased with moisture content of chamomile samples. Average specific energy consumption, energy efficiency and energy loss varied in the range 18.93–28.15 MJ kg^{-1} water, 8.25–13.07% and 16.79–26.01 MJ kg^{-1} water, respectively, while the best energy results were obtained at 400 W, 50 °C and 0.5 m s^{-1}.

1. Introduction

Drying of agricultural and food materials requires considerable amounts of energy. The high cost of energy provides a strong incentive to invent processes that will use energy efficiently. In most industrialized countries, the energy used in drying accounts for 7–15% of the nation's industrial energy consumption, often with relatively low thermal efficiencies ranging from 25% to 50% (Akpinar et al., 2005).

Convective air-drying is the most common method for drying of agricultural materials. Because of the low thermal conductivity of food materials in the falling rate drying period, heat transfer to the inner sections of foods during conventional heating is limited. Also, conventional drying results in low overall efficiency, approximately 30%. In such dryers, around

* Corresponding author. Tel.: +98 9121304520; fax: +98 21 44292200.
E-mail address: Minaee@modares.ac.ir (S. Minaei).
Peer review under responsibility of King Saud University.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.jssas.2014.11.003
1658-077X

Nomenclature

Ar	cross sectional area (m^2)
a_i	coefficients of Eq. (1)
a, b, c, d, k	constants
C_a	specific heat of air (J kg^{-1} °C^{-1})
D_{eff}	effective diffusivity (m^2 s^{-1})
E_c	energy consumption (J)
E_{CS}	specific energy consumption (J kg^{-1} water)
ER	evaporation rate (g water min^{-1})
L	half thickness of layer (m)
MR	moisture ratio (dimensionless)
MR_{exp}	experimental moisture ratio
MR_{pre}	predicted moisture ratio
m_t	mass of sample at time t (g)
m_{t+dt}	mass of sample at time t + dt (g),
m_w	mass of evaporated water (kg)
n	constant, positive integer
P	microwave power (W)
P_v	saturation vapor pressure (mbar)
P_0	standard atmosphere pressure (mbar)
Q_f	air flow rate (kg s^{-1})
R^2	coefficient of determination
RH	relative humidity
RMSE	root mean square error
T	temperature (°C)
t	time (s)
u	air velocity (m s^{-1})
W	moisture loss of sample (kg)
X	sample moisture content (kg water kg^{-1} dry matter)
X_0	initial moisture content (kg water kg^{-1} dry matter)
X_e	equilibrium moisture content (kg water kg^{-1} dry matter)
Z	number of coefficients and constants
ΔT	temperature difference of inlet and outlet air (°C)

Subscripts

out	outlet
in	inlet
t	at any time

Greek symbols

λ_w	latent heat of free water (J kg^{-1})
λ_{wp}	latent heat of product (J kg^{-1})
η_{en}	energy efficiency (%)
χ^2	reduced chi-square
ρ_a	density of air (kg m^{-3})

35–45% of energy input is wasted as hot air exhaust (Tippayawong et al., 2008). The desire to alleviate these problems, to prevent significant quality deterioration, as well as to achieve fast and effective thermal processing has resulted in the increasing use of microwaves for food drying of agriculture products.

Comparison of the convectional convective method with combined microwave-convective, showed that combined systems can shorten the drying period of biological materials significantly, without causing a decline in the quality of the dried product (Alibas et al., 2007). In the microwave-convective drying method, forced air is supplied to carry away the water vapor, driven from the interior of the food to its surface by the microwave action. To prevent condensation of the driven moisture on the surface of the food, it is necessary to heat the air to increase its moisture carrying capacity (Sharma and Prasad, 2004).

The most important aspect of drying technology is the mathematical modeling of the drying process and equipment. Its purpose is to allow design engineers to choose the most suitable operating conditions and then size the drying equipment and drying chamber accordingly to meet the desired operating conditions (Darvishi et al., 2013).

The objectives of this study were to: (1) describe the influence of microwave-convective drying conditions on drying kinetics of chamomile; (2) select optimal thin-layer drying models for drying process; (3) evaluate the drying energy aspects (specific energy consumption, energy efficiency, energy loss), and (4) to compute the effective moisture diffusivity for chamomile.

2. Materials and methods

2.1. Material

Chamomile leaves were obtained from a farm in the vicinity of Tehran, Iran. All the samples were refrigerated at 4 ± 0.5 °C before being dried. The average initial moisture content of Chamomile leaves was determined to be 83 ± 0.5%, wet basis, using the gravimetric method. During the drying experiments, mean range of ambient temperature was 30 ± 2 °C and mean relative humidity was 28 ± 3%.

Figure 1 Image of the experimental apparatus.