Energy 34 (2009) 1594–1602

Contents lists available at ScienceDirect

Energy

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

Mathematical modelling of the thin layer solar drying of banana, mango and cassava

Kamenan Blaise Koua [a,*], Wanignon Ferdinand Fassinou [a], Prosper Gbaha [b], Siaka Toure [a]

[a] Laboratoire d'Energie Solaire, Université de Cocody- Abidjan, 22 BP 582 Abidjan 22, Cote d'Ivoire
[b] Laboratoire d'Energie Nouvelle et Renouvelable, Institut National Polytechnique, Félix HOUPHOUET – BOIGNY de Yamoussoukro (COTE D'IVOIRE)

ARTICLE INFO

Article history:
Received 14 February 2009
Received in revised form
4 June 2009
Accepted 4 July 2009
Available online 24 July 2009

Keywords:
Plantain banana
Mango
Cassava
Thin layer
Mathematical modelling
Statistical analysis
Effective diffusivity

ABSTRACT

The main objectives of this paper are firstly to investigate the behaviour of the thin layer drying of plantain banana, mango and cassava experimentally in a direct solar dryer and secondly to perform mathematical modelling by using thin layer drying models encountered in literature. The variation of the moisture content of the products studied and principal drying parameters are analysed. Seven statistical models, which are empirical or semi-empirical, are tested to validate the experimental data. A non-linear regression analysis using a statistical computer program is used to evaluate the constants of the models. The Henderson and Pabis drying model is found to be the most suitable for describing the solar drying curves of plantain banana, mango and cassava. The drying data of these products have been analysed to obtain the values of the effective diffusivity during the falling drying rate phase.

1. Introduction

Lots of countries in the world encounter food problem. Near the problem of new energy sources, there is, nowadays the competition between energy and food crops placing further pressure on available agricultural land. But food crops, when they are produced, have problems of storage and conservation.

It is known that in many rural areas in the developing countries, there is no electricity to use refrigeration for the conservation of agricultural products. Therefore, one of the promising methods of their conservation is drying technique. It is the case for many areas of Africa, Asia, Caribbean, and Latin America.

Drying products as a means of improving preserving and storage has been practiced for many centuries. Dry products can be stored for months or even years without appreciable loss of nutrients [1], compared to fresh products which can only be kept for a few days under ambient conditions. In the food sector, many studies have been lead to optimize the drying operation [2–4] by rationalizing energy consumption and improving the quality of the dried product. In this regard, solar drying is an adequate solution for developing countries which are poor in conventional energy resources but have an important solar input practically during all the year [4,5]. Solar energy is preferred because it is abundant, free, inexhaustible and non-polluting. It can be tapped at relatively low cost and has no associated environmental dangers [6]. Its use instead of the other energies (electrical, heating…) is a way to save energy and to valorise it. Using a solar dryer, the drying time can be shortened by 65% compared to sun drying because, inside the dryer, it is warmer than outside; the quality of the dried products can be improved in terms of hygiene, cleanliness, safe moisture content, colour and taste; the product is also completely protected from rain, dust and insects [6].

The study of the drying behaviour of different products has recently been a subject of interest for many researchers on both theoretical and application grounds. Many studies concerning drying processes are reported in literature [7–9]. Many researches on the mathematical modelling and experimental studies have been conducted on the thin layer solar drying processes of various agricultural products [10–16].

This paper deals with three tropical products: cassava, mango and plantain banana. They have some characteristics which are summarised as follows.

Cassava (*Manihot escuenta*) is a perennial shrub of the Euphorbiaceae family, native of South America, in particular the tableland of Guyana. It is now widely cultivated and harvested as annual plant in

* Corresponding author: Tel.: +1 225 05 84 64 28; fax: +1 225 22 44 04 12
E-mail address: kouakb@yahoo.fr (K.B. Koua).

0360-5442/$ – see front matter
doi:10.1016/j.energy.2009.07.005

Nomenclature

A_s	specific surface of the product (m^2/kg)
A_w	activity of water
D_{eff}	effective diffusivity (m^2/s)
h_c	surface heat transfer coefficient (J/sm^2 K)
h_m	mass transfer coefficient (J/hr .m^2 Pa)
L	half thickness of the product (m)
L_v	latent heat of water vaporization (J/kg)
m	mass (kg)
R	water vapour constant (J/kg K)
R_{ds}	overall resistance to diffusion (m^2 s/kg)
S_p	surface of the product (m^2)
T_a	drying air temperature (°C)
T_p	product temperature (°C)
t	time (s)
X	moisture content (g water/g dry basis)
W_m	average absolute moisture

Subscripts

cr	critical
eq	equilibrium
f	final
h	hygroscopic
0	initial
r	ratio

the tropical and subtropical regions. Cassava is becoming an increasingly important input in animal feed and human diet in West Africa [17]. Roa [17] reports that cassava provides approximately 8–10% of the calories that man requires. Cassava tubers are processed in various ways for human consumption.

Mango belongs to the genus Mangifera, consisting of numerous species of fruit trees in the flowering plant family Anacardiaceae. Mango is grown in all tropical and subtropical countries of the world. It is the sixth most produced fruit in the world (after sweet banana, grape, orange, apple and plantain banana). It is rich in β-carotene, fiber, minerals and vitamins.

Plantain Banana (*Musa paradisiaca*) is the fruit of an herbaceous perennial plant. It is widely cultivated in many African countries and in many other parts of the world including Caribbean, Central and South America. Rich in starch, fiber, minerals (especially potassium, magnesium, iron and zinc) and in vitamin B, plantain banana is a very nutritious food that is easily digested.

The three previous products have high moisture content at harvest and therefore cannot be preserved for more than a few days under ambient conditions of 20–25 °C [1]. Although, refrigeration would be an ideal way of preserving banana plantain, cassava and mango in its fresh form, in developing countries, lots of people do not have the possibility to get refrigerators [1] and it is therefore necessary to use solar energy to dry them.

The three products concern eating habits of people who are several millions in tropical and subtropical regions of the world. Dry cassava can be used by humans, animals and can also be used to produce bio-oil for automotive as in China [18]. Cassava dry chips and banana dry chips are crushed to make flour which is used to prepare meals for human. Mango dry chips are put in hot water for few minutes to be hydrated before to be eaten. Dried mangoes and dried cassava are packed and exported to Europe and to America by African farmers.

In this study, the thin layer drying behaviour of banana, mango and cassava in a direct solar dryer are investigated. Additionally, the mathematical models describing the thin layer drying curves is determined by non-linear regression analysis. An approximation of the diffusion model is selected to obtain the drying curve equation of the three products.

Finally, the purpose of this paper is to provide a response to the conservation of the products studied. The application of the experimental device and the model tested is directed for the rural parts of Ivory Coast but also for all countries in the world (Africa, Asia, Caribbean, Latin America…) which have the same climate as Ivory Coast. The results obtained can help not only researchers in the world who need some news about banana, cassava and mango chips but also local and multinational industries to design solar dryers for all countries where the products studied are grown.

2. Mathematical formulations

2.1. Drying kinetics

The physical phenomena study, during the drying process, is very complex. This complexity is due to the transfer study of mass, heat, vapour and liquid depending on the temperature gradients. It is the reason why the approach is usually empirical. It consists in studying the moisture content variation of the product during the drying.

The curve obtained experimentally is the variation, during the drying, of the product moisture content, X, as a function of time. However, there are three possible representations:

- the moisture content, X, with time, t,
- the drying rate, $(-dX/dt)$, with the time, obtained by calculating the derivative (dX/dt) directly from the experimental data,
- the drying rate, $(-dX/dt)$, with the moisture content.

The analysis of a drying rate curve highlights three distinct phases of drying:

- putting temperature into the product,
- a constant drying rate phase,
- a falling drying rate phase.

The transitional phase of temperature input corresponds to the rise in temperature of the product; up to attaining the wet bulb temperature which is a characteristic of the drying environment. This phase is generally very short with regard to the overall drying time and is not available for all products. Therefore, this brief period of rising temperature is not taken into account the analysis of drying rate curve. In the dryer, this period corresponds to the stoving phase.

First phase: constant drying rate phase

This phase describes a rapid movement of free water by capillary from inside the product to its surface. During this phase, the drying rate does not depend on the nature of the product but only on drying conditions. The moisture content X tends to X_{cr} which is the critical moisture content. During this phase, the product remains at the wet bulb temperature.

This phase is generally considered as an adiabatic drying. In the equilibrium condition, the rate of the water removal from the surface of the product is equal to the rate of heat transfer to the surface [19,20]:

$$L_v \frac{dm}{dt} = h_c S_p (T_a - T_p) \quad (1)$$