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Simulation of solar drying of grapes using an integrated heat and mass transfer model

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ABSTRACT

A mathematical model was developed to simulate solar drying of grapes, integrating heat and mass transfer models solved by an explicit finite differences method, considering changing boundary conditions. The model simultaneously incorporated shrinkage of the product, changes in effective moisture diffusivity and dependence of thermal properties on water content and temperature. Field experiments were carried out in a mixed mode solar dryer located in the North of Portugal, with pre-blanched grapes. A good prediction of experimental solar drying curves was attained. The mathematical model can be applied for simulating solar drying of different foods, once known their specific thermo-physical properties. Simulations obtained with the developed model can be valuable for predicting accurate drying times and consequently to design, control and optimise the production of dried foods.

1. Introduction

The transformation of grapes into raisins started in the Middle East in ancient times. They were later traded in the Mediterranean Sea by the Phoenicians, Romans and Greeks. Nowadays, raisins have a large applicability in a wide range of products such as breakfast cereals, dairy, bakery and confectionery products and nutritional bars. They may be produced in tunnel dehydrators or by using solar energy, which are the most applied methods worldwide. Producing raisins using solar energy is a contribution to the increasing society demand on renewable energies for a sustainable world. There are two methods of using solar energy for crop drying: sun and solar drying. Sun drying comprehends the direct exposure of products to the sun. The products are placed on the ground in the open air and their temperature is raised by direct absorption of incident radiation. In solar drying, the solar energy is captured by some process to rise the temperature of the drying air [1] (Fuller, 1993) and air flows through the product by natural or forced convection [2] (Ratti and Mujumdar, 1996). In general, both methods involve high labour costs and solar drying also requires a higher equipment investment. Nevertheless, solar drying has some advantages: it is more hygienic, because products are protected from dust, insects and rodents, and products spoilage by moulds is prevented, since products are also protected from the rain.

Mathematical modelling of drying is essential for predictive and simulation purposes and for the design of drying equipment. Drying is a complex phenomenon, simultaneously involving heat and mass transfer. The added difficulty in modelling solar drying processes lies on the changes of meteorological conditions during the entire process. Solar radiation intensity has a great variability [3] (Mühlbauer and Esper, 1999), depending on the hour of the day, season of the year and weather conditions. The incident radiation on a covered solar dryer originates a greenhouse type effect [4] (Brennan, 1994). Solar radiation penetrates the dryer transparent cover, being transmitted (almost all) to the foodstuff inside the chamber, which is heated. On the other hand, the heat emitted by the heated foodstuff cannot 'escape' from the dryer, because it has longer wavelengths [5] (Holman, 1986). Meteorological conditions alter air conditions inside the solar dryer (temperature, humidity and velocity), usually generating a daily cyclic behaviour. The temperature of the dryer increases from dawn until sunset.

Until the eighties, most of the mathematical models that describe solar drying were developed assuming constant inlet air conditions and products shrinkage was often neglected [6] (Ratti

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Nomenclature

a, b, c	model parameters (Eq. (7))
a_w	water activity
A_p	projected area of the product (m^2)
A_s	surface area of the product (m^2)
Bi	Biot number
Bi_m	Biot number for mass transfer
C	Guggenheim constant
C_0, K_0	pre-exponential factors of C and K of Eq. (8)
Cp	specific heat of the product ($KJ\ kg^{-1}\ K^{-1}$)
D	moisture diffusivity ($m^2\ s^{-1}$)
D_0	pre-exponential parameter of moisture diffusivity ($m^2\ s^{-1}$)
F	geometry factor
g_N	daylength
$\overline{h}$	average convective heat transfer coefficient ($J\ s^{-1}\ m^{-2}\ K^{-1}$)
h_D	convective mass transfer coefficient ($m\ s^{-1}$)
H_1, H_m, H_q	parameters of C and K of Eq. (8)
i	node
I	radiation flux density ($J\ s^{-1}\ m^{-2}$)
J_N	global radiation in the Nth day ($J\ m^{-2}$)
K	factor that corrects properties of the multilayer molecules with respect to the bulk liquid
Kp	thermal conductivity of the product ($W\ m^{-1}\ {}^{\circ}C^{-1}$)
m	total mass of the product (kg)
m_w	mass of evaporated water (kg)
N	climatological day number
Qc	convective heat loss ($J\ s^{-1}$)
Qe	evaporative heat loss ($J\ s^{-1}$)
Qr	radiation heat loss ($J\ s^{-1}$)
r	radial position
R	average equivalent radius (m)
Rg	universal gas constant ($8.314\ J\ mol^{-1}\ K^{-1}$)
RH	air relative humidity (%)
t	time (s or min)
t_d	fractional part of a day time
T	product temperature (K)
T_1	product temperature (°C)
T_a	air temperature (K)
W	average water content on wet basis ($kg_{water}\ kg_{wet\ matter}^{-1}$)
$\overline{X}$	average water content on dry basis ($kg_{water}\ kg_{dry\ matter}^{-1}$)
X	water content on dry basis ($kg_{water}\ kg_{dry\ matter}^{-1}$)
Xe	equilibrium water content on dry basis ($kg_{water}\ kg_{dry\ matter}^{-1}$)
Xm	monolayer water content ($kg_{water}\ kg_{dry\ matter}^{-1}$)
y	year angle

Greek symbols

α	absorptivity of solar radiation
δ	solar declination
Δt	time interval (s)
Δr	space interval (m)
ε	emissivity
λ	latent heat of vaporization ($J\ kg^{-1}$)
ϕ	latitude (°)
σ	Stefan–Boltzmann constant ($5.6704 \times 10^{-8}\ W\ m^{-2}\ K^{-4}$)

Subscripts

0	initial value
av	average value
r	at radius r
t	at time t

and Mujumdar, 1997). The models have however been improved, taking into consideration heat and mass transfer phenomena under time-varying conditions. The products shrinkage phenomena as well as the variation of physical and thermal properties of the products as a function of their moisture content and temperature have been included in models that describe drying processes of potatoes and grapes [7,8] (Youcef-Ali et al., 2001; Bennamoun and Belhamri, 2006). Phoungchandang and Woods (2000) [9] included terms for solar absorption, long-wave emission, natural or forced convection, and evaporation in the simulation of solar drying of bananas. However, the above mentioned studies may be upgraded in order to integrate product shrinkage, the variation of mass transfer parameters with moisture content and meteorological aspects.

These limitations open up research opportunities, since there is still much to be done concerning the development of mathematical models, precise and accurate in the description of drying processes.

The main objective of this work was to develop a mathematical model for simulation of solar drying of grapes. The model integrates heat and mass transfer phenomena, shrinkage of the product, as well as mass diffusivity and thermal properties dependence on water content and temperature under variable boundary conditions. The daily meteorological aspects were taken into consideration. The model was validated with experimental field solar drying data and represents an advance for the accurate prediction of the drying of grapes, contributing to the design of more efficient processes.

2. Modelling considerations

Solar drying of grapes involves simultaneously heat and mass transfer phenomena. The heat transfer model must take into account convection, evaporation and radiation, with meteorological effects included in the radiation term. The mass transfer process can be considered diffusion-controlled.

2.1. Heat transfer model

When a product is submitted to sun drying or in a direct or mixed-mode solar dryer, the overall energy balance to the product can be described by Ref. [9] (Phoungchandang and Woods, 2000):

$$\frac{d\,(m\,Cp\,T)}{dt} = \alpha\,A_p I(t) - \overline{h}\,A_s(T - T_a) - \frac{d\,(\lambda\,m_w)}{dt} - A_s\,\varepsilon\,\sigma\,F\,\left(T^4 - T_a^4\right) \tag{1}$$

The left term of the previous equation corresponds to the rate of energy gained by the dried product, and the parcels in the right side are the absorbed radiant energy, the convective heat loss, the evaporative heat loss and the radiation heat loss, respectively.

I(t) is the radiation flux density at a certain day time, and may be obtained through meteorological records. When the recording time interval is very large, it may be shortened through appropriate meteorological models. A model developed by Charles-Edwards and Acock (1977) [10] can be adopted, taking into