Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
International Journal of Heat and Mass Transfer 48 (2005) 561–572
International Journal of HEAT and MASS TRANSFER
www.elsevier.com/locate/ijhmt

Numerical simulation of conjugate heat and mass transfer process within cylindrical porous media with cylindrical dielectric cores in microwave freeze-drying

Zhi Tao [a,*], Hongwei Wu [a,b,1], Guohua Chen [b,2], Hongwu Deng [a,1]

[a] *National Laboratory on Aero-engines, School of Jet Propulsion, Beijing University of Aeronautics and Astronautics, Beijing, China*
[b] *Department of Chemical Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*

Received 26 June 2003; received in revised form 10 September 2004

Abstract

This paper presents a numerical model for the process of microwave freeze-drying within a cylindrical porous media with cylindrical dielectric cores. The set of transient governing equations developed are solved numerically with variable time-step finite volume method. Analysis of numerical results may lead to following main conclusions for the new freeze-drying process: (1) Proper usage of cylindrical dielectric cores could dramatically reduce the drying time. (2) The loss factor ε'' of the cylindrical dielectric core is an important parameter influencing the drying behavior. (3) Two sublimation fronts do exist within the porous media due to the existence of inner dielectric cores. (4) The impact of cylindrical dielectric cores on drying could not be ignored even though the initial saturation is low ($S_0 = 0.2$).

Keywords: Heat and mass transfer; Freeze-drying; Porous media; Cylindrical dielectric core; Loss factor

1. Introduction

Freeze-drying (lyophilization) is used as a gentle dehydration method for heat sensitive materials especially in food and pharmaceutical industries, usually for the purpose of preservation. It is well known for its ability to sustain the high quality of products (colour, shape, aroma, texture, biological activity, etc.) than any other drying methods due to its low processing temperature and no oxygen involved in the process. Other advantages of freeze-drying include its protection against chemical decomposition, ease of rehydration, etc. However, freeze-drying is an expensive dehydration process because of low drying rates, high capital and energy costs generated by refrigeration and vacuum systems, and relatively long drying time required [1–5]. As a consequence, the use of freeze-drying on the industrial scale is restricted to high added-value products. Freeze-drying by microwave heating, however, has proven to overcome those disadvantages as it has the characteristic

* Corresponding author. Tel.: +86 10 8231 7443; fax: +86 10 8231 7432.

E-mail addresses: tao_zhi@buaa.edu.cn (Z. Tao), hongwei_wu@hotmail.com (H. Wu), kechengh@ust.hk (G. Chen), deng.yy@263.net (H. Deng).

[1] Tel.: +86 10 8231 4545.

[2] Tel.: +852 2358 7138; fax: +852 2358 0054.

0017-9310/$ - see front matter
doi:10.1016/j.ijheatmasstransfer.2004.09.008

Nomenclature

a	coefficient
A	area, m^2
b	source term
c	specific heat, J/(kg °C)
D	diffusivity, m^2/s
E	electric field strength, V/m
f	frequency, MHz
ΔH	sublimation latent heat of ice, J/kg
I	vapor source intensity, kg/(m^3 s)
J	mass flux, kg/(m^2 s)
J_{vs}	mass flux of vapor in icy region, kg/(m^2 s)
K_D	permeability, m^2
K_r	relative permeability,
m	mass, kg
P	pressure, Pa
P_R	vacuum pressure, Pa
q	density of microwave power absorbed, J/(s m^3)
r	polar coordinate direction
R	water vapor gas constant, $m^2/(s^2 K)$
R_d	radius of cylindrical dielectric core, m
R_P	initial radius of porous material, m
S	saturation (ice volume)/(void volume)
t	temperature, °C
T	temperature, K
T_R	vacuum temperature, K
u	velocity, m/s
u_{sat}	moisture content, kg/(m^3)
V	volume, m^3

Greek symbols

α	heat transfer coefficient, W/(m^2 °C)
ε	porosity
ε'	permittivity, F/m
ε''	loss factor
ϕ	generalized variable
λ	thermal conductivity, W/(m °C)
μ	viscosity, kg/(m s)
ρ	density, kg/m^3
τ	time, s
ξ	small value

Subscripts

0	initial
1	first sublimation front
2	second sublimation front
a	with cylindrical dielectric core
b	without cylindrical dielectric core
d	cylindrical dielectric core
e	effective
f	sublimation front
F	final time
i	ice
I	initial time
nb	neighbor
p	current control volume
s	solid body
v	vapor
w	wall of porous material

of heating up materials volumetrically. Experiments and numerical predictions all showed that the microwave freeze-drying appears to be one of the most promising techniques to accelerate the rate of dehydration and enhance overall quality [6–14].

Copson, in 1962, firstly modeled the microwave freeze-drying process with pseudo steady- state assumption that had been used in conventional freeze-drying modeling. Much efforts have been devoted afterwards to this area by many researchers [7,15,10,11,16,17]. Ma and Peltre [18] presented a transient one-dimensional model, which was the first transient analysis of microwave freeze-drying. A more general analysis was undertaken by Ma and Peltre [10,11] to improve the accuracy of the Copson model, and was later extended to be two-dimensional by Ang et al. [12] to take into account of the material anisotropy. Chen et al. [19] studied volatile retention in microwave freeze dried model foods. Wang and Shi [20–24] developed a model which took into account the sublimation or condensation by vapor transport in the unsaturated frozen region, and saturation change was considered. Further research on microwave freeze-drying focused on optimization of combined radiant and microwave aided freeze-drying [17] and solid entrainment [25,26].

Although ordinary microwave freeze-drying could dramatically accelerate the drying process, it has much room to be enhanced further by adding dielectric cores to the porous materials to be dried. The dielectric core is functioning an another heat source because the dielectric core has to be properly selected high loss factor than ice so that the microwave energy will be mainly taken by the core during drying. In this way, the porous material will be heated from both inside and outside at the same time, which could remarkably increase the drying process. Adding dielectric cores is, therefore, a novel, interesting, and also industrially relevant drying technique. Wu et al. [27] presented a double sublimation front model within spherical porous media with dielectric cores in microwave freeze-drying. By now, there is not a single report on using dielectric materials within cylindrical porous media in microwave freeze-drying.

In the present study, a numerical simulation is carried out to investigate the microwave freeze-drying with