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Convective control to microwave exposure of moist substrates. Part II: Model validation and application

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ABSTRACT

This paper is the second of set of two dealing with exposure of moist substrates to electromagnetic energy, while providing localized convection heat and mass transfer. Solution of the comprehensive model lead to the electric distribution in the cavity–substrate ensemble, the velocity distribution in the cavity and around the substrate, and the temperature and residual moisture distributions in the substrate.

The model has been successfully validated against the available experimental values, with few temperature degrees of difference, only. It was found that the dielectric loss which dictates the local energy absorption depends inversely on the local temperature, for the devised treatments.

For the two extremal treatments, the volume-averaged moisture varies by some 20% only, but in one case hot spots up to 1000 K were induced at the surface, otherwise jet impingement with Reynolds number of 32k allowed to cool off the surface to as low as 300 K.

1. Introduction

In many thermal processes to bio-substrates, combined heat and mass (liquid water and water vapor) are transferred within the sample and through its free surface to the environment, driven by temperature and concentration differences, respectively; and water phase change that occurs, affects such combination. Interaction with convection, which takes a variety of patterns and thermal regimes, develops locally on the free surface according with the equipment configuration, operation and the product shape, and can be used to enhance and control the process. Additional physics mechanisms are often employed, such as the exposure to electromagnetic energy or microwaves (MW) at the common 2.45 GHz nominal frequency, as recently reviewed by Rakesh et al. [1].

Nowadays a common option in material processing, MW exposure still needs to be studied in details, especially when combined with other transfer phenomena. With bio-substrates being characterized by low thermal conductivity, MW heating may exhibit a certain non-uniformity in the temperature distribution, leading to local overheating or even run-away loci. These problem can be alleviated exploiting localized forced convection or jet impingement (JI), as indicated first by Geedipalli [2]. This combination of physics was then proposed by the first Part of the present work De Bonis et al. [3], featuring a conjugate approach which does not rely upon empirical heat transfer coefficients. A discussion on how the appropriate management of JI may influence the distribution of temperature in a moist substrate in a MW cavity was then reported by Pace et al. [4] based on experiments. These data have been employed here, in order to validate the present model. Besides this few literature items, no reference to the problem at stake was found that reflect the aforementioned complex coupling.

The comprehensive model presented in the first Part of the paper De Bonis et al. [3] is exploited here and applied to a number of configurations, to explore for the first time some interesting scenarios: for example, cooler or stronger air jets are used to damp or mitigate the excessive local temperature rise (and consequent local water loss), for otherwise uncontrolled MW exposures. Consequently, the surface moisture is depleted with a different degree of uniformity depending on the inherent thermal and fluid dynamics driving forces. Surface- and volume- averaged temperatures, and volume-averaged moisture, are also computed with process time and discussed, as well as the interconnections among the variety of transport phenomena and the adopted feature of the conjugate formulation.

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Nomenclature

c	species concentration
c_p	constant pressure specific heat
d	diameter
D	binary water-substrate mass diffusivity
$\mathbf{D}$	electric flux density
$\mathbf{E}$	electric field intensity
f	frequency
$\mathbf{H}$	magnetic field intensity
K	rate of evaporation
M	molecular weight
n	MW working cycles
p_a	outlet pressure
P_0	nominal MW power
Re	Reynolds number, based on jet nozzle
Q	thermal flux
t	time
T	temperature
U	air specific humidity
$\mathbf{v}$	velocity
x, y, z	coordinates
X	moisture content

Greek

Δh_{EV}	latent heat of evaporation
Δt_{OFF}	MW resting time
Δt_{ON}	MW working time
ε_0	permittivity of free space
ε_r	complex relative permittivity
ε'	dielectric constant
ε''	relative loss factor
λ	thermal conductivity
ρ	density
ρ_e	charge density
σ_c	effective electrical conductivity

Subscripts

0	in free space
a	working air
EV	evaporation
i	initial
j	jet
l	liquid water
MW	microwave
s	substrate, bulk
S	surface- averaged
v	water vapor
V	volume-averaged

Superscript

a	air, conjugate formulation
s	substrate, bulk, conjugate formulation

2. Transport phenomena interconnections in relation with substrate properties

The model presented in the first Part (to which the Reader is referred for all details), has been tuned up by comparing the computational results with the experimental data reported by Pace et al. [4].

It is suitable here to summarize on the interconnections between the various *transport phenomena* for the process at stake, and emphasize on the importance of adoption of proper substrate dielectric properties. Let us recall first the Ampère's law and the Gauss's laws for the electric field:

$$\nabla \times \mathbf{H} = \left(\varepsilon_0 \varepsilon_{\mathrm{r}} \frac{\partial}{\partial t} + \sigma_c\right)\mathbf{E}; \qquad \nabla \times \mathbf{D} = \nabla \times \varepsilon_0 \varepsilon_{\mathrm{r}} \mathbf{E} = \rho_e \tag{1}$$

These equations are complemented by Faraday's law and Gauss's law for the magnetic field (*electromagnetic transport*). The dielectric property, which concurs to alter the MW power absorption by the substrate, is the relative permittivity, ε_r:

$$\varepsilon_r = \varepsilon' - \imath\varepsilon'' \tag{2}$$

with ε' the relative dielectric constant, and ε'' the relative loss factor.

Due to the electromagnetic perturbation in the dielectric substrate, given by the direct irradiation and the cavity reflections, some of the nominal cavity power, P_0, is converted in MW absorbed power, Q_{MW}:

$$Q_{\mathrm{MW}} = \pi f \varepsilon_0 \varepsilon'' |\mathbf{E}|^2 \tag{3}$$

An increase of ε'' with respect to ε' in Eq. (2) enhances the heat conversion in moist substrates: for example, if a higher moisture concentration is found locally in the substrate, ε'' would grow larger locally, and the absorbed power Q_{MW} is found to increase accordingly. That is why the following form of Eq. (2) is generally suggested as reviewed by Malafronte et al. [5]:

$$\varepsilon_r(T, c_{\mathrm{l}}) = \varepsilon'(T, c_{\mathrm{l}}) - \imath\varepsilon''(T, c_{\mathrm{l}}) \tag{4}$$

Here the liquid water concentration c_{l} is to be found by applying the following mass (species) equation in the substrate (*moisture transfer*):

$$\frac{\partial c_{\mathrm{l}}}{\partial t} = \nabla \cdot (D \nabla c_{\mathrm{l}}) - K c_{\mathrm{l}} \tag{5}$$

In the present model the concentration of liquid water is kinetically linked, via the latent heat of evaporation $Q_{\mathrm{EV}} = M \Delta h_{\mathrm{EV}} K c_{\mathrm{l}}$, to the distribution of temperature, which is solved by the energy equation in the substrate (*heat transfer*):

$$\rho_{\mathrm{s}} c_{p\mathrm{s}} \frac{\partial T}{\partial t} = \nabla \cdot (\lambda_{\mathrm{s}} \nabla T) + Q_{\mathrm{MW}} - Q_{\mathrm{EV}} \tag{6}$$

which reveals the two-way relationship between temperature and moisture distributions, and electric field distribution in the process at stake. Finally, a further interdependence mechanism is represented by the energy equation in the working air:

$$\rho_{\mathrm{a}} c_{p\mathrm{a}} \frac{\partial T}{\partial t} + \rho_{\mathrm{a}} c_{p\mathrm{a}} \mathbf{v} \cdot \nabla T = \nabla \cdot (\lambda_{\mathrm{a}} \nabla T) \tag{7}$$

where the distribution of velocity, $\mathbf{v}$, must be solved by imposing the stationary Navier–Stokes equations, along with the pertinent turbulent closure relationships (*momentum transfer*).

Finally, proper conjugate conditions are devised along the substrate exposed surface: energy and vapor continuity is allowed, during processing. Denoting with the superscripts (a) and (s) respectively the cavity air and substrate sides across such interface:

$$T^{\mathrm{s}} = T^{\mathrm{a}}, \quad c_{\mathrm{v}}^{\mathrm{s}} = c_{\mathrm{v}}^{\mathrm{a}} \tag{8}$$

3. Case nomenclature and explored effects

In this paper, a number treatments were devised which resulted in vigorous exposure to MW, yet with two different patterns of intermittency, under the constant application of moderately or