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Combined microwaves and convection heating: A conjugate approach

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ABSTRACT

Microwave treatment has been gaining increasing recognitions in the food industry and household frameworks alike. Better energy and finishing efficiencies can be obtained by adding an additional transport mechanism, such as forced air convection heating. In this work, transient distributions of temperature and moisture during the combined treatment is analyzed by a full computational fluid dynamics model, coupled with custom moisture diffusion and evaporation notations.

Non-linear, interdependent transfer phenomena equations are discussed, and the multi-physics effects are emphasized. Realistic transfer exchanges are inherently considered by using a conjugate approach and no resort to empirical, averaged heat and mass transfer coefficients is made. A validation with the experimental results from the available literature has been brought forth, for potato disks drying by either pure convection, pure MW exposure or both mechanisms combined. The effect of process time and working air velocity on the local temperature distributions are finally presented.

1. Introduction

One of the most common operation in cooking and food conditioning, microwaves (MWs) exposure still needs to be studied in details, especially when combined with other heating treatments. In spite of doubts raised on the food safety due to possible structural changes, the mild effect and the versatility, that seemingly reduce the thermal impact on food functional properties, allow for an overall food quality improvement.

MWs heating involves drying of a solid–fluid mixture or food substrate, its physical mechanism being different than the conventional drying, in that the phase change is induced in the latter by a thermal perturbation, applied on the substrate's external surface by forced air, whereas the driving mechanism within the substrate is the sole classical heat conduction. MWs heating acts directly instead in the food proper, as it is given by the interaction between electromagnetic field and dipolar molecular species, such as water, or ionic, such as salts: the friction produced by the dipoles rotation and by the migration of ionical species to regions of opposite charge generates heat, specially where the water content is in relative excess (Romano et al., 2005; Marra et al., 2009).

Drying by MWs offers then several distinct benefits including increasing throughput and higher energy efficiency, but its intensity (penetration depth) depends on physical and dielectric properties of the treated food and can vary with temperature (Venkatesh and Ragavan, 2004), electromagnetic field frequency, as well as with food composition and its overall shape (Marra et al., 2009).

Heating by MW is recognized as a rapid treatment, but nonetheless it is characterized by a certain non-uniformity in the temperature distribution. In fact, depending on the specific product's penetration depth, overheating loci can be attained near the sample's core, as in the case of food cylinders with a diameter smaller than a critical value, or higher or even runaway temperatures in the vicinity of the outer layers, as in the case of a flat plates or cylinders with characteristic lengths above a critical value (Romano and Marra, 2008). The uneven temperature distribution, similar to a damped sinusoidal function, is also noteworthy (Ayappa et al., 1991; McMinn et al., 2003; Haghi and Amanifard, 2008).

Additional non-uniformity promotion can result, especially on the external surface, from the evaporation of water and the convective thermal effects due to flow conditions that are established in the air around the sample. Clearly, then, the appropriate management of flow conditions of the surrounding air may influence the distribution of temperature in the material and the heating effects to the sample.

MW heating-induced drying is also a most interesting case in which the classic approach based on empirical, average transfer rates of energy and mass (Boldor et al., 2005; Haghi and Amanifard, 2008) should be overcome. A conjugate approach can be employed instead, implying that heat and mass transfer can be solved simultaneously in both the subject substrate and the surrounding air.

Moreover, forced air convection can be profitably supplemented inducing a desired superficial finish (Geedipalli et al., 2008), but the transfer phenomena must be coupled and intertwined, due to

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Nomenclature

A	pre-exponential factor in Eq. (10) (1/s)
c	concentration (mol/m^3)
$c_{1\varepsilon}$	model parameter in Eq. (16)
$c_{2\varepsilon}$	model parameter in Eq. (16)
c_μ	model parameter in Eqs. (17),(23), (24)
c^+	model parameter in Eq. (24)
c_p	specific heat (J/kg K)
E_a	activation energy in Eq. (10) (J/mol)
$\mathbf{g}$	gravitational acceleration (m/s^2)
f	dimensionless energy distribution in Eq. (2)
H	height, thickness (m)
k	turbulent kinetic energy (m^2/s^2)
K	rate of production of evaporation in Eq. (10) (1/s)
M	molecular weight (g/mol)
$\mathbf{n}$	normal versor
p	pressure (Pa)
Q	volumetric power (W/m^3)
r	reflection coefficient
R	universal gas constant (J/mol K)
t	time (s)
T	temperature (K)
$\mathbf{v}$	velocity vector (m/s)
x	lateral coordinate (m)
X	moisture content (kg/kg db)
z	vertical coordinate (m)

Greek symbols

α	attenuation factor (1/m)
β	phase factor (1/m)
β_T	thermal expansion coefficient (1/K)
ϵ'	relative dielectric constant
ϵ''	relative loss factor
δ_w	distance from surface (m)
δ_w^+	dimensionless distance from surface
Δh	latent heat (J/kg)
ε	turbulent energy dissipation rate (m^2/s^3)
κ	Von Kàrmàn's constant
λ	thermal conductivity (W/mK)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
σ_k	model parameter in Eq. (16)
σ_ε	model parameter in Eq. (16)
τ	transmission coefficient
ω	radian frequency of MW radiation (Hz)

Subscripts

0	nominal, reference
a	air
EV	evaporation
l	liquid water
MW	microwave
p	process
s	sample
t	turbulent
v	water vapor

the coexistence of heating mechanisms, the evaporation of the free water from and within the substrate and the related diffusion of water vapor, the macroscopic transport and elimination of such vapor from the same substrate.

In the recent past, few contributions only have been focusing upon such coupling, and this especially for the drying of food. In this paper such conjugate approach, featuring the full coupling and interdependence of aforementioned mechanisms, is proposed. A full conjugate model of a drying food was presented by De Bonis and Ruocco (2007), yet for a specific exchange configuration (a thin baking product to be dried by an impinging turbulent jet draft), where the focus was on residual local water activity. This approach, holding the potential of the generality as no empirical correlation are used at the interfaces, has been then exploited recently by Curcio et al. (2008) and De Bonis and Ruocco (2008) for classical parallel-flow configurations.

Magee and co-workers (Khraisheh et al., 1997, 2000; McMinn et al., 2003) have reported on MW drying aided by convection, including some considerations related to MW drying in a fludized bed (then for a non-flow system with bulk properties), while management strategies and control of industrial drying tunnel assisted by MW were presented by Cheng et al. (2006). Then again, Zhang and Datta (2005) have used CFD modeling to locally assess the value of Nusselt number in a common MW oven, speculating on the importance of the ventilation strategy to obtain an improved product.

Based on the literature review, it is evident that a generalized approach to the combined heating and drying, holding the potential of process optimization, is lacking. This work was therefore aimed to establish a theoretical approach, able to combine such different heating mechanisms (convective and MWs), and to describe the fundamentals of optimized food conditioning with a full conjugate approach, and with inference to a kinetics-based evaporation. Such an approach allowed for the assessment, in this preliminary study, of the influence of some driving parameters (the combined convection-MW drying arrangement, the velocity of the working air and the process duration) on the overall conditioning process (the thermal and moisture distribution within the sample).

2. Analysis

2.1. Assumptions

The purpose of this paper is to solve the local heat transfer problems due to the combination of MWs and forced convection treatment, under some benchmark configurations. To this end, a food sample of given size ($L_s' \times H_s$) is exposed to both MWs and classical air drying convection, in a two-dimensional dryer cavity of given size ($L_p \times H_p$), as presented in Fig. 1 (with $L \gg H$). To analyze multiple transport phenomena, the following assumptions are considered:

1. the food sample is placed in an electromagnetically shielded cavity;
2. the sample's upper surface only is open to MW radiation, assumed of uniform intensity;
3. the drying air is incompressible, and with temperature-dependent properties;
4. the sample is homogeneous and isotropic; its dielectric properties are considered constant, the thermal conductivity and mass diffusivity are considered to be temperature-dependent while specific heat and density are considered both temperature- and moisture-dependent;
5. the viscous heat dissipation in the drying air is neglected;