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Convective control to microwave exposure of moist substrates. Part I: Model methodology

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ABSTRACT

This paper is the first of set of two dealing with a multidimensional, multiphase and multiphysics model of conjugate and coupled transport phenomena during electromagnetic treatments to moist substrates. Exposure to electromagnetic energy can be controlled and optimized by providing localized convection heat and mass transfer. The model features the stationary Maxwell's equation, coupled to the transient equations of heat conduction and mass diffusion. Moreover, the stationary Navier–Stokes equations are devised, in conjunction with the energy and mass convective equations, as the dependence on the localized heat and mass convection is accounted for. Energy and vapor transport are applied regardless of the substrate interface, to exploit the advantages of a conjugate formulation. An optimized kinetic formulation is employed to deal with water phase change.

Due to the complex interdependence of the various transport phenomena, a computational strategy is set up to solve the model, by means of a finite element code which is run in a cycle of 2 consecutive sweeps, depending on the assumption of the dielectric properties of the substrate. Grid independence tests gave acceptable results for more than 0.5 M elements and more than 5 M degrees of freedom. This paper sets the grounds for the presentation of selected results, reported in Part II.

1. Introduction

Often associated with almost water-saturated conditions, bio-products are commonly found, bearing active compounds whose valuable features need to be preserved. When seeking their stability, drying is employed to lower moisture in order to avoid microbial spoilage, extend product stability, enhance quality and promote ease of handling. Under drying, partial evaporation of the liquid phase occurs within substrate and at its free surface, yielding a vapor phase which is removed.

Traditionally, drying is performed by an auxiliary flow of warm, dry air around and past moist samples, simultaneously promoting heat and mass transfer which are inevitably found to be strongly intertwined, i.e. coupled and competing, through the evaporation. The modeling tasks get soon quite complex when refer to realistic configurations, nevertheless the scientific interest has recently increased [1]. But physics mechanisms other than plain convection 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 [2] for generic bio-products and by [3,4] for foodstuff. In this way, even more complex formulations easily come up.

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. Conversely, MW heating acts directly within the moist sample, for the friction produced by the dipoles rotation and by the migration of ionic species to regions of opposite charge generates volumetric heat, specially where the liquid water is in relative excess [5,6].

Nowadays a common option in material processing, MW exposure still needs to be studied in details, especially when combined with other transfer phenomena, but also when substrate's functional properties are at stake [7]. Processing by MWs offers

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Nomenclature

A	pre-exponential factor
$\mathbf{B}$	magnetic flux density
c	species concentration
c_p	constant pressure specific heat
d	diameter
D	binary mass diffusivity
$\mathbf{D}$	electric flux density
$\mathbf{E}$	electric field intensity
E_a	activation energy
f	frequency
f_γ	turbulence parameter in Eq. (20)
f_γ^*	turbulence parameter in Eq. (21)
$\mathbf{H}$	magnetic field intensity
k	turbulent kinetic energy
K	rate of evaporation
M	molecular weight
$\mathbf{n}$	normal versor
p	pressure
p_a	outlet pressure
P_0	nominal MW power
P_k	turbulent production term
Q	thermal flux
R	universal gas constant
S	surface
t	time
T	temperature
U	air specific humidity
$\mathbf{v}$	velocity
x, y, z	coordinates
X	moisture content

Greek

α	turbulent constant in Eq. (19)
β	propagation constant
γ, γ^*	turbulent constants in Eq. (19)
γ_0	turbulent constant in Eq. (20)
γ_0^*	turbulent constant in Eq. (21)
Δh_{EV}	latent heat of evaporation
ε_0	permittivity of free space
ε_r	complex relative permittivity
ε'	dielectric constant
ε''	relative loss factor
λ	thermal conductivity
μ	dynamic viscosity
μ_0	permeability of free space
μ_r	relative permeability
μ_t	turbulent dynamic viscosity
ρ	density
ρ_e	charge density
σ_c	effective electrical conductivity
σ, σ^*	turbulent constants in Eq. (19)
ξ, ζ	dimensionless lengths
Φ	mean rotation-rate tensor
χ_k	turbulent parameter in Eq. (21)
χ_ω	turbulent parameter in Eq. (20)
Ψ	mean strain-rate tensor
ω	specific dissipation rate

Subscripts

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

Superscript

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

then several distinct benefits including increasing throughput and higher energy efficiency, but its intensity and penetration depth depends on physical and dielectric properties of the substrate and can vary with temperature [8], frequency, as well as with composition and shape [5]. With bio-products 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 forced convection, but then a more complex analysis (as mentioned above) is needed to take into account the inherent non-uniformity of the flow field. Modeling the coupling of MW and heat transfer to substrate samples through bulk forced convection has attracted many researchers so far. Early attempts include [9–15] for one-dimensional, simplified geometries. For more realistic geometries, [16–21] had contributed with increasing details and physics descriptions, but some empirical heat and mass transfer coefficients were systematically employed, therefore their accounts cannot serve to the interested Readership for different, general formulations and configurations. From the heat and mass transfer standpoint, a clear need therefore exists for a comprehensive model, with the potential of applicability in any possible situation, such as the one proposed in the present work.

When an air jet is issued from a proper nozzle onto a substrate, jet impingement (JI) results which is well known for its superior transport characteristics. In many application JI offers process intensification and control even for moist substrates, as suggested by [22], where an up-to-date review on this technique is also offered. [23] first indicated how JI can be profitably employed to induce a desired superficial finish to a MW treatment. This analysis, however, was again hindered by the specification of an empirical heat transfer coefficient at the free surface, which can vary considerably instead under JI. Mathematical modeling that goes beyond a simplistic lumped behavior, incorporating the inherent variabilities of each phenomena at stake (exposure to MW, air flow, heat and mass diffusion and convection, phase change) is therefore desirable, but remains a considerable task especially for the their coupling and interdependence, as recently pointed out by [4]. Recently, multiphase transport and coupled heat and mass transfer in a porous medium using the Maxwell's equations in a microwave was proposed by [2], but no flow field was solved with its interaction with thermal and moisture field, therefore their results cannot be used and the application of their model is impeded. A discussion on how the appropriate management of JI may influence the distribution of temperature in a moist substrate in a MW cavity was also reported by [24] based on experiments. Besides this few literature items, no reference to the problem at stake was found that reflect the aforementioned complex coupling.