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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.

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## 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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# 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.

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## 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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