CFD/Electromagnetics Interactions Via Realistic Heat and Mass Transfer to Moist Substrates

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Introduction: Experiments were performed in a prototype with *jet impingement and microwave* [1]. Microwave treatments are nowadays common to a variety of biotech substrates, which are initially partially *saturated with water*. Jet impingement is an effective option for process control and enhancement. *Quality & Safety* of the final substrate are at stake: selected targets such as residual vitamins, surface texture, appearance, microbial inactivation need to be properly quantified.

Realistic modeling helps understand the involved multiphysics: the exposure to *electromagnetics* (even for complex shapes) is joined to *convective and conductive heat transfer* and *diffusive mass transfer* (for water and other target properties, treated as chemical species). Some of these transport phenomena are coupled via the *evaporation of inherent liquid water*.

Computational Method: Jet impingement and microwave exposure to a blunt substrate are modeled in a given cavity configuration.

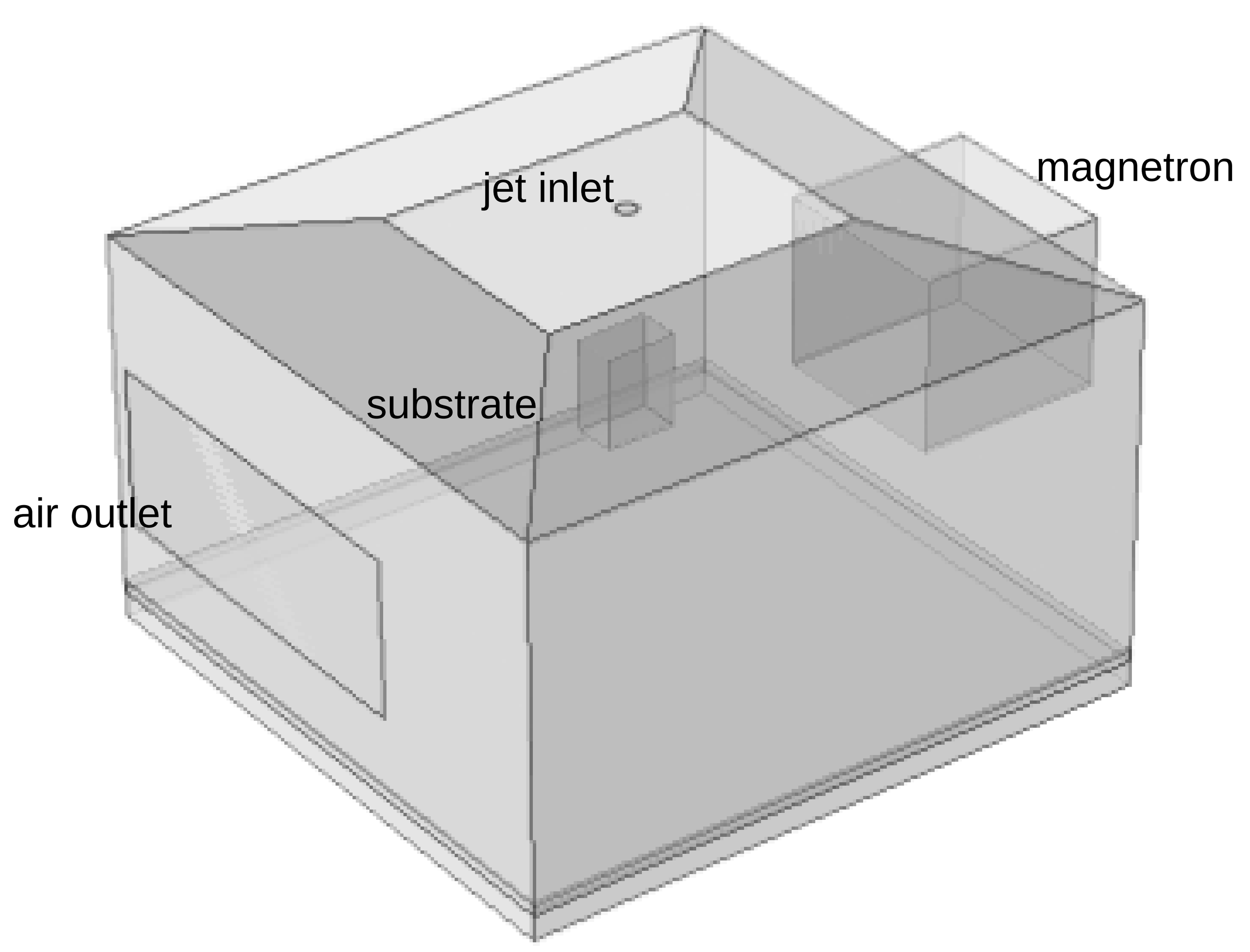


Figure 1. Rendering of the experimental rig, with views of the magnetron box at right, the jet inlet at top, the substrate at the center of the cavity, and the outlet of spent air at left

The heat and mass fluxes vary seamlessly through the substrate's surface (*conjugate modeling*), with no need for empirical assumptions. A kinetics approach is employed for evaporation of water. Subscripts a, s, l and v stand for air, substrate, liquid and vapor, respectively; the other symbols having their usual meaning [2,3].

Maxwell's Equations:

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t}$$

$$\nabla \times \mathbf{H} = \left(\varepsilon_0 \varepsilon_r \frac{\partial}{\partial t} + \sigma_c\right)\mathbf{E}$$

$$\nabla \times \mathbf{D} = \nabla \times \varepsilon \mathbf{E} = \rho_e$$

$$\nabla \times \mathbf{B} = \nabla \times \mu \mathbf{H} = 0$$

Energy Equations:

$$\rho_a c_{pa} \frac{\partial T_a}{\partial t} + \rho_a c_{pa} \mathbf{v} \cdot \nabla T_a = \nabla \cdot (\lambda_a \nabla T_a)$$

$$\rho_s c_{ps} \frac{\partial T_s}{\partial t} = \nabla \cdot (\lambda_s \nabla T_s) + P - Q_{EV}$$

$$P(x, y, z, t) = \frac{1}{2} \omega \varepsilon_0 \varepsilon'' |\mathbf{E}|^2$$

$$Q_{EV} = M \Delta h_{EV} K c_l \qquad K = A \exp\left(\frac{E_a}{RT_s}\right)$$

Navier-Stokes Equations:

$$\rho_a \frac{\partial \mathbf{v}}{\partial t} + \rho_a \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla p + \nabla \cdot (\mu_a + \mu_t)\left[\nabla \mathbf{v} + (\nabla \mathbf{v})^T\right] \qquad \nabla \cdot \mathbf{v} = 0$$

Liquid and vapor transfer Equations:

$$\frac{\partial c_l}{\partial t} = \nabla \cdot (D \nabla c_l) - K c_l \qquad \frac{\partial c_v}{\partial t} = \nabla \cdot (D \nabla c_v) + K c_l \qquad \frac{\partial c_v}{\partial t} + \mathbf{v} \cdot \nabla c_v = \nabla \cdot (D \nabla c_v)$$

An *iterative strategy* has been devised in the Model Builder to account for inherent variation of relative permettivity ε_r with temperature and water content. First, the CFD/EM/HT+CHDS are solved in sequence, with constant ε_r; then, the run is restarted with EM/HT+CHDS allowing for property variation.

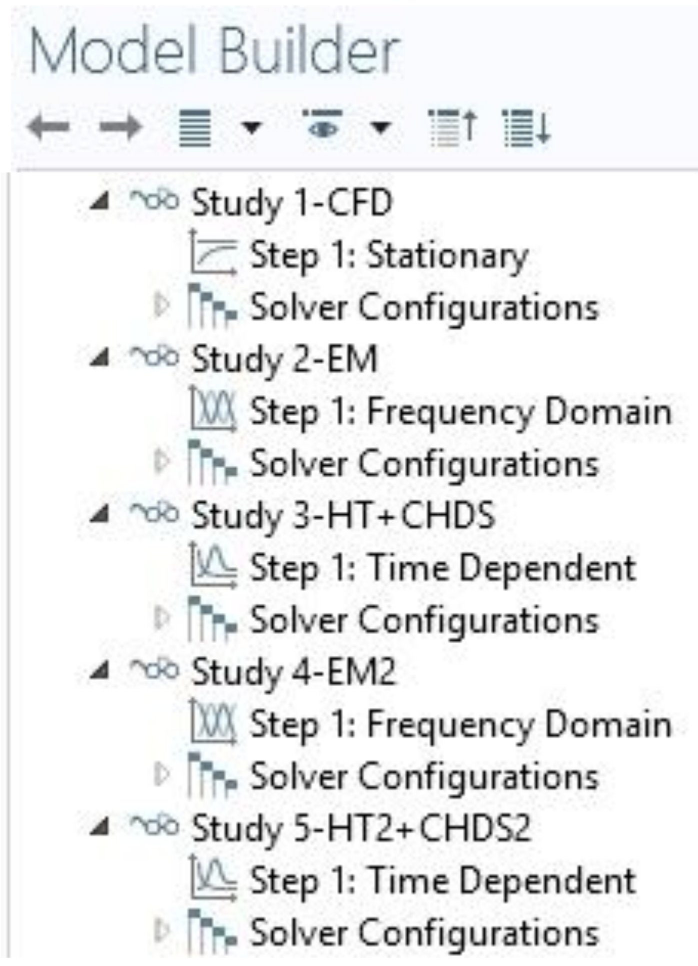
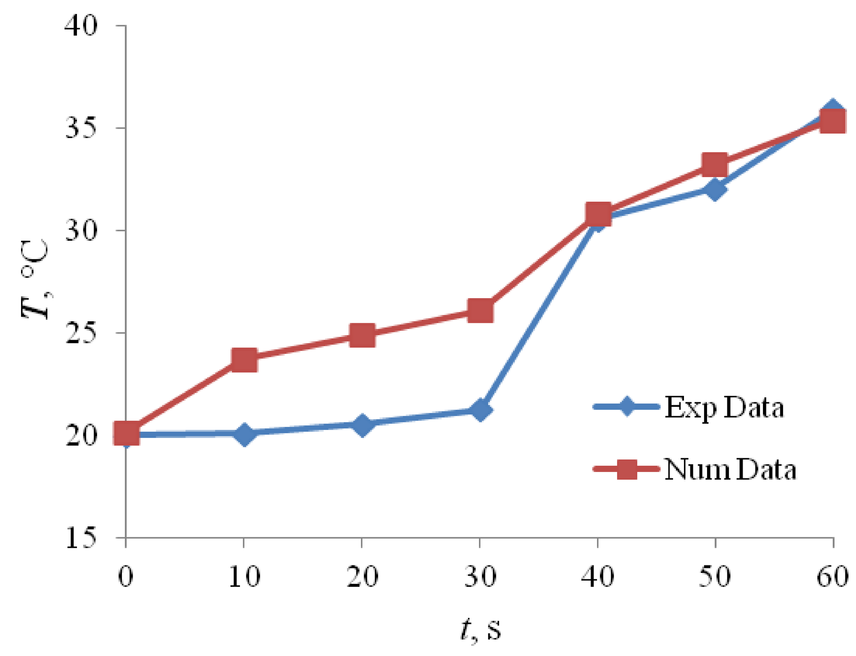


Figure 2 (right). The sequence of Studies in the Model Builder, in order to solve the dependence of electromagnetic properties on *T* and *c*



Results: Trials have been conducted with pulsed microwaves and impinging jets which works to *mitigate and address surface finish*.

Figure 3 (left). The validation of computed temperature in the center of substrate, with corresponding experimental measurements [1]

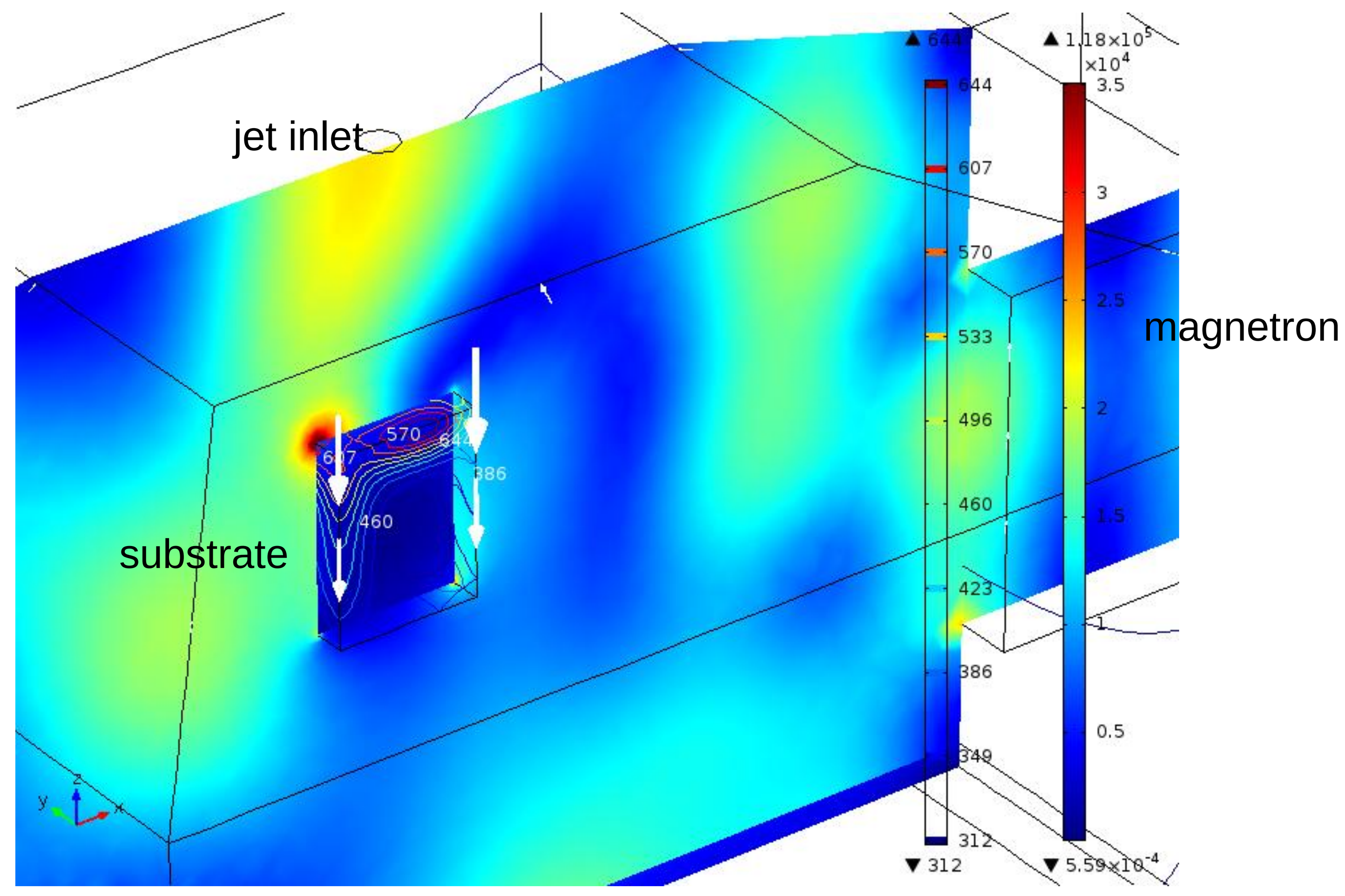


Figure 4. A vertical central slice along *x*: map of the electric field norm, contour of temperature and arrows of impinging air velocity

Conclusions: More efforts are under way to complete the virtualization. With the use of jet impingement, the envisaged multiphysics will increase treatment throughput, and improve energy consumption and product Quality & Safety. These good, positive outcomes should encourage operators to embrace the microwave-enhanced cold jet impingement technology.

Acknowledgements
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References:

1. M. Pace, M.V. De Bonis, F. Marra, G. Ruocco, Characterization of a combination oven prototype: Effects of microwave exposure and enhanced convection to local temperature rise in a moist substrate, International Communications in Heat and Mass Transfer 38 557-564 (2011)
2. M.V. De Bonis, G. Ruocco, Conjugate heat and mass transfer by jet impingement over a moist protrusion, International Journal of Heat and Mass Transfer 70 192-201 (2014)
3. G. Ruocco, F. Marra, M.V. De Bonis, Modeling radio frequency heating using computational fluid dynamics, in: G.B. Awuah, H.S. Ramaswamy, J. Tang (Eds.), Radio frequency heating in food processing: principles and applications, CRC Press, New York, 2014