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 electromagnetic (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.

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

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

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.

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References:

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:
\[ \nabla \times E = -\mu \frac{\partial H}{\partial t} \]
\[ \nabla \times H = (\varepsilon_0 \varepsilon_r \frac{\partial E}{\partial t} + \sigma J) \]
\[ \nabla \times D = \nabla \times \sigma E = \mu J \]
\[ \nabla \times B = \nabla \times \mu H = 0 \]

Energy Equations:
\[ \rho aC_p a \frac{\partial T_a}{\partial t} + \rho aC_p s \nabla \cdot (a v T_s) = \nabla \cdot (\lambda_a \nabla T_a) \]
\[ \rho L aC_p l \frac{\partial T_l}{\partial t} = \nabla \cdot (\lambda_l \nabla T_l) + P - Q_{\text{EV}} \]
\[ P(x,y,z,t) = \frac{1}{2} \sigma_0 |\mathbf{E}|^2 \]
\[ Q_{\text{EV}} = M \Delta h_{EV} K \]
\[ K = A \exp \left( \frac{E_a}{RT_c} \right) \]

Navier-Stokes Equations:
\[ \frac{\partial \mathbf{v}}{\partial t} + \nabla \cdot (a \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \cdot (a \mu \nabla \mathbf{v}) + \nabla \cdot \left( \nabla \mathbf{v} + (\nabla \mathbf{v})^T \right) \]
\[ \nabla \cdot \mathbf{v} = 0 \]

Liquid and vapor transfer Equations:
\[ \frac{\partial C_l}{\partial t} = \nabla \cdot (D \nabla C_l) - K \]
\[ \frac{\partial C_v}{\partial t} = \nabla \cdot (D \nabla C_v) + K \]
\[ \frac{\partial C_l}{\partial t} + \nabla \cdot (a v C_l) = \nabla \cdot (D \nabla C_l) \]