Multiphysics Simulation for Microwave Drying Spherical Materials

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Introduction

- Microwave drying of fruits and vegetables has been found to result in large textural changes in the product such as puffing, crack formation and even burning due to the inhomogeneous heating of the microwaves
- Microwave drying of potatoes is a complex interplay of mass, momentum and energy transport.
- Three phases are considered in the system: solid (skeleton), liquid (water) and gas (water vapor and air).
- Concentration of different species was solved for using the Transport of Dilute Species module (for liquid water) and Maxwell-Stefan Diffusion model (for vapor and air) together with Darcy Law (to calculate Gas Pressure).
- Microwave oven worked in 10% power level (Cycle Way). Shrinkage effects have been ignored.

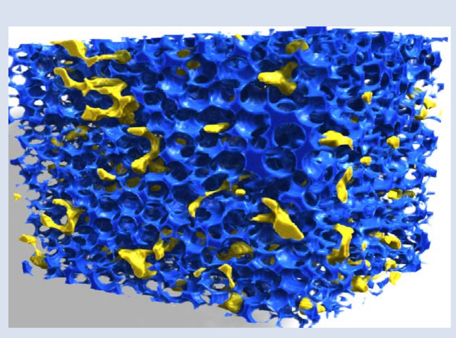
Modeling Framework

Transport Model

- **Conservation of energy**
  - Bulk flow
  - Conduction
  - Phase change
- **Conservation of mass**
  - **Water**: bulk flow, capillary flow and phase change
  - **Gas** (air, vapor): bulk flow phase change, binary diffusion
- **Conservation of momentum**
  - Darcy's flow

Electromagnetic Model

- **Maxwell's Equations**
  - Faraday's Law of Induction
  - Ampere's Law
  - Gauss Law for electricity
  - Gauss Law for magnetism
- **Power Dissipation**
  - Poynting Theorm



Potatoes treated as a porous material

Governing Equations

Conservation of Mass

Water: $$\frac{\partial c_w}{\partial t} + \nabla\cdot(c_w \mathbf{v_w}) = \nabla\cdot(D_w \nabla c_w) - \dot{I}$$

Gas: $$\frac{\partial c_g}{\partial t} + \nabla\cdot(c_w \mathbf{v_w}) = \dot{I}$$

Vapor: $$\frac{\partial c_v}{\partial t} + \nabla\cdot(c_w \mathbf{v_w}) = \nabla\cdot\left(\varphi S_g \frac{C^2}{\rho_g} M_a M_v D_{eff,g} \nabla x_v\right) + \dot{I}$$

Conservation of Energy

$$\frac{\partial}{\partial t}\left[\sum_{i=s,w,v,a}(c_i c_{p,i} T)\right] + \sum_{i=w,v,a}(\mathbf{v_i} - \mathbf{v_s})\cdot\nabla(c_i c_{p,i} T) + \sum_{i=w,v,a}(c_i c_{p,i} T \nabla\cdot\mathbf{v_i}) - c_{p,w} T \nabla\cdot(D_c \nabla c_w) = \nabla(k_{eff}\nabla T) - \lambda \dot{I}$$

Conservation of Momentum

Darcy's Law: (water and gas) $$\mathbf{v}_i = -\frac{k_i k_{r,i}}{S_i \phi_i \mu_i}\nabla P$$

Maxwell's Equation

Faraday's Law of Induction: $\nabla\times\mathbf{E} = j\omega\mu\mathbf{H}$

Ampere's Law: $\nabla\times\mathbf{H} = -j\omega\varepsilon_0\varepsilon^*\mathbf{E}$

Gauss Law for electricity: $\nabla\cdot(\varepsilon\mathbf{E}) = 0$

Gauss Law for magnetism: $\nabla\cdot\mathbf{H} = 0$

Power Dissipation

Poynting Theorm: $$P(\mathbf{x},T) = \frac{1}{2}\omega\varepsilon_0\varepsilon''(\mathbf{E}\cdot\mathbf{E}^*)$$

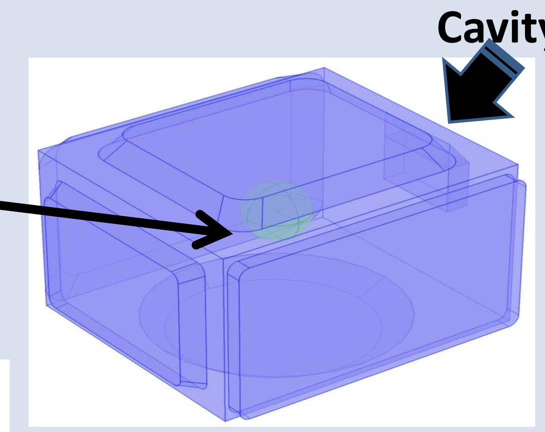
Methodology

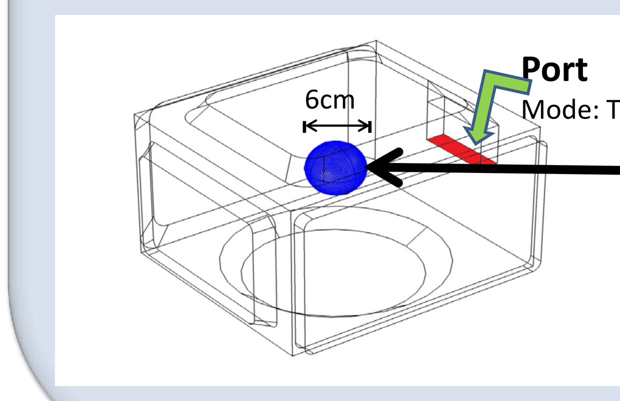
Geometry & Boundary Conditions

Microwave oven model
GE JES738WJ02

Potato Sample (Green)
Diameter: 6cm

PEC (Blue boundary)
Perfect Electric Conductor





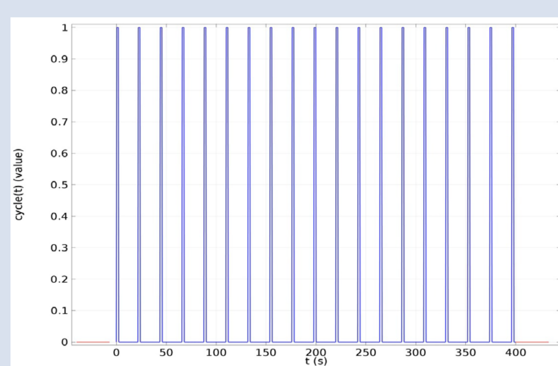
Boundary Conditions
- Forced convection heat transfer
- Moisture loss through evaporation

Results

The coupled Electromagnetic and Transport Model developed above was solved by FEM method to obtain the moisture content ,temperature et al.

10% Power Level Cycle Heating

The microwave oven input power reduced by the cycle way



The microwave oven works in 10% power level

- **Input Power (10%)**

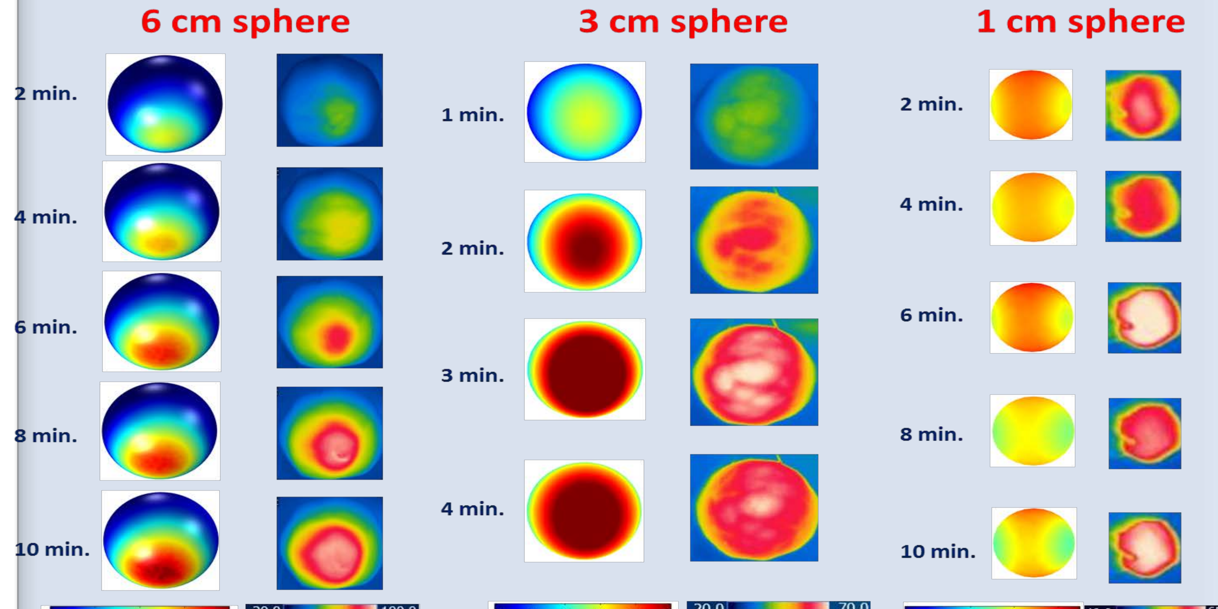
Cycle Time: 22s

Microwave Heating Time: 2s

Temperature Profile

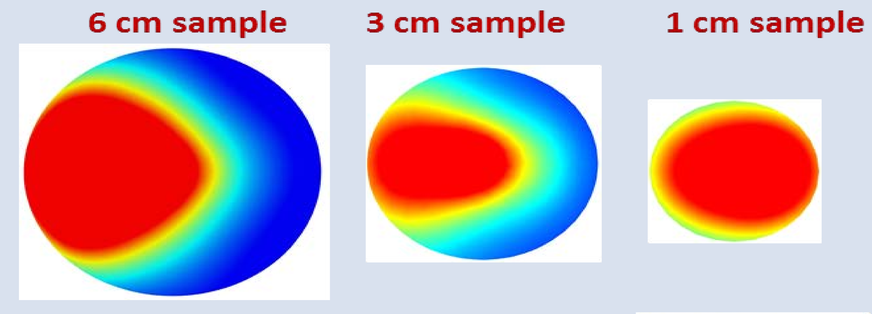
Temperature

Simulated and experimental surface temperature

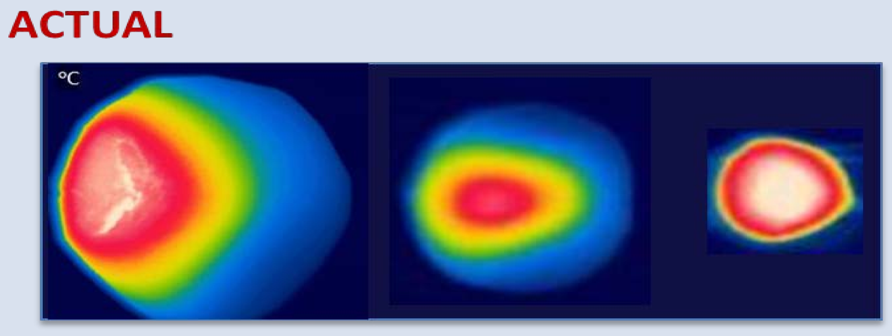


Temperature profiles of cross-section validations by infrared camera:

SIMULATED

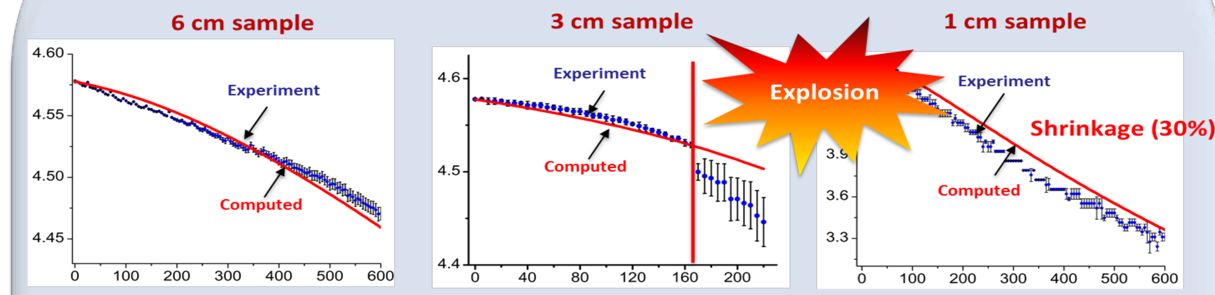


ACTUAL

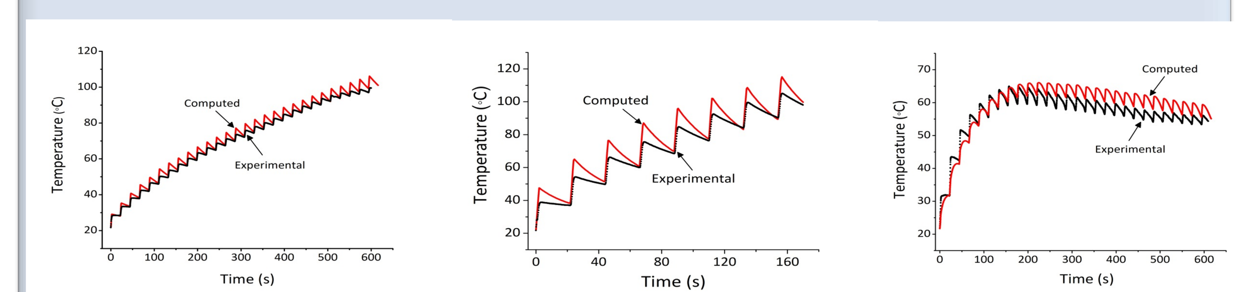


Regions of high temperatures shift away from the center with increasing size

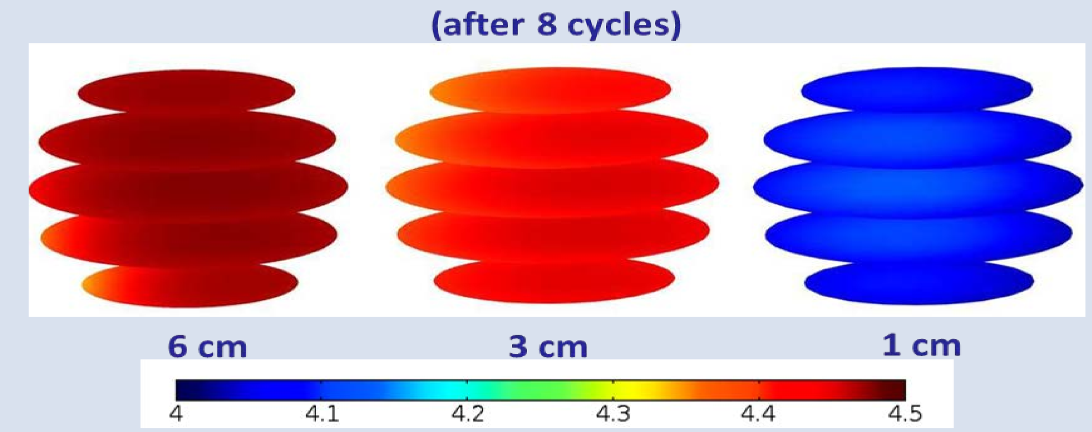
Moisture Content



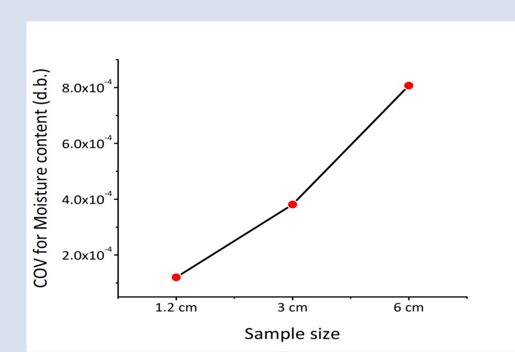
Temperature profiles validated by optical thermometer

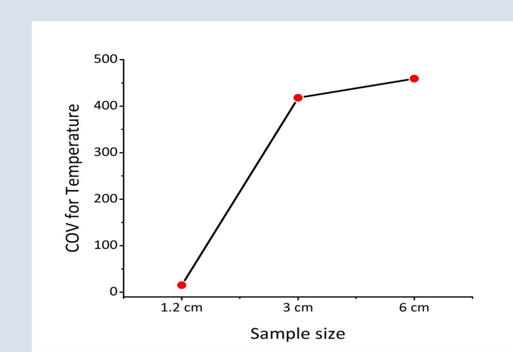


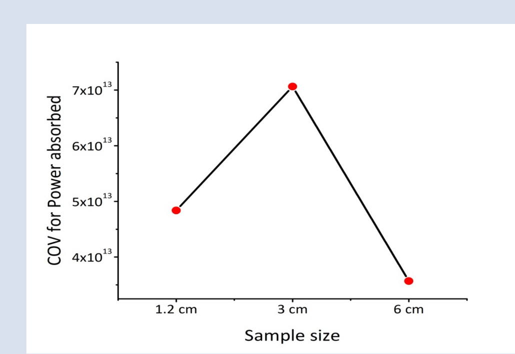
Simulated Moisture Distribution (after 8 cycles)

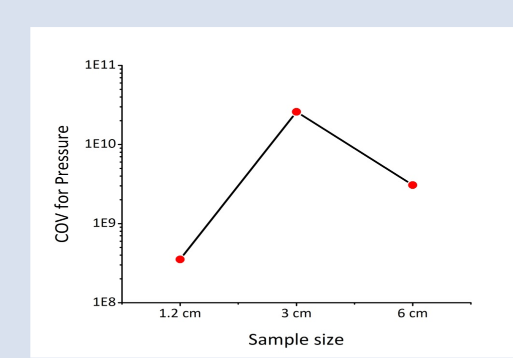


Coefficient of varition

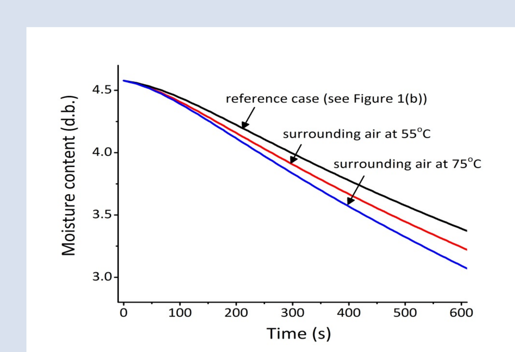


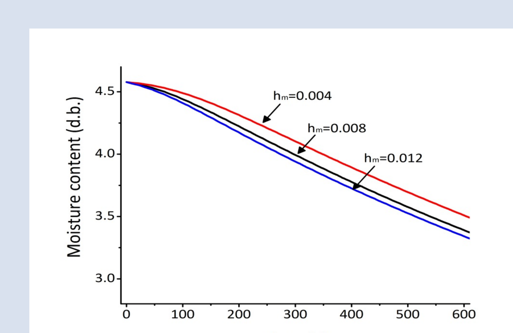


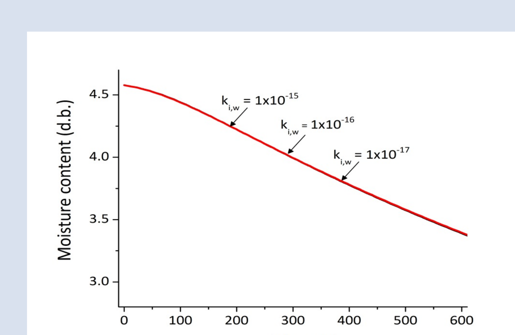


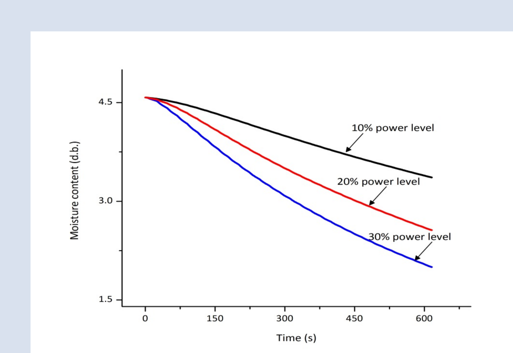


Sensitive Analysis









Conclusion

- A mechanistic approach that predicts the microwave drying process of potatoes has been developed
- The model could aid in predicting key quality attributes associated with the microwave drying process

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