Modeling the Effect of Headspace Steam on Microwave Heating Performance of Mashed Potato

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University of Nebraska – Lincoln

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Session : Electromagnetic Heating

COMSOL CONFERENCE
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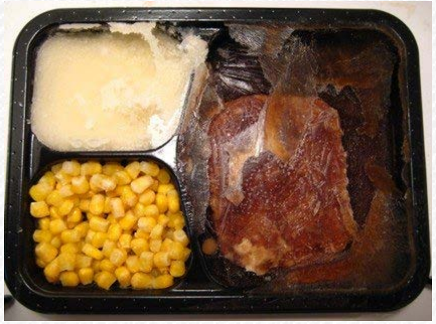
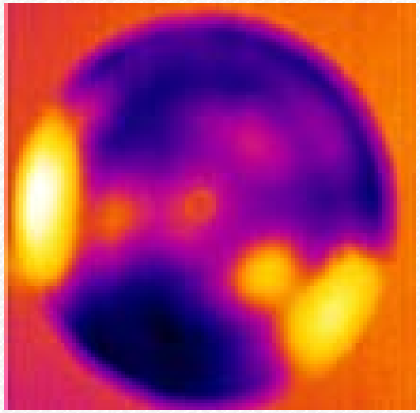
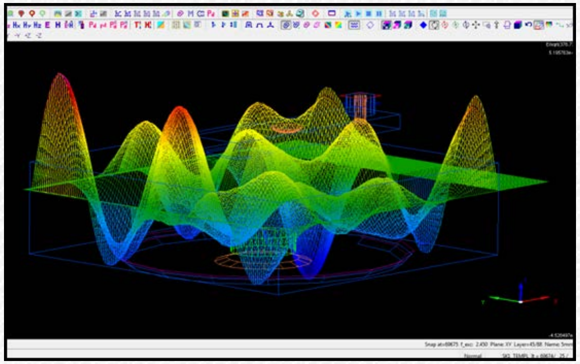
Microwave Heating
Convenient but Non-uniform







Microwave Heating Models

Computer model use science based approach for :

– product formulation

– design product layout

– design package

– develop cooking instructions

Novel Food Product Development

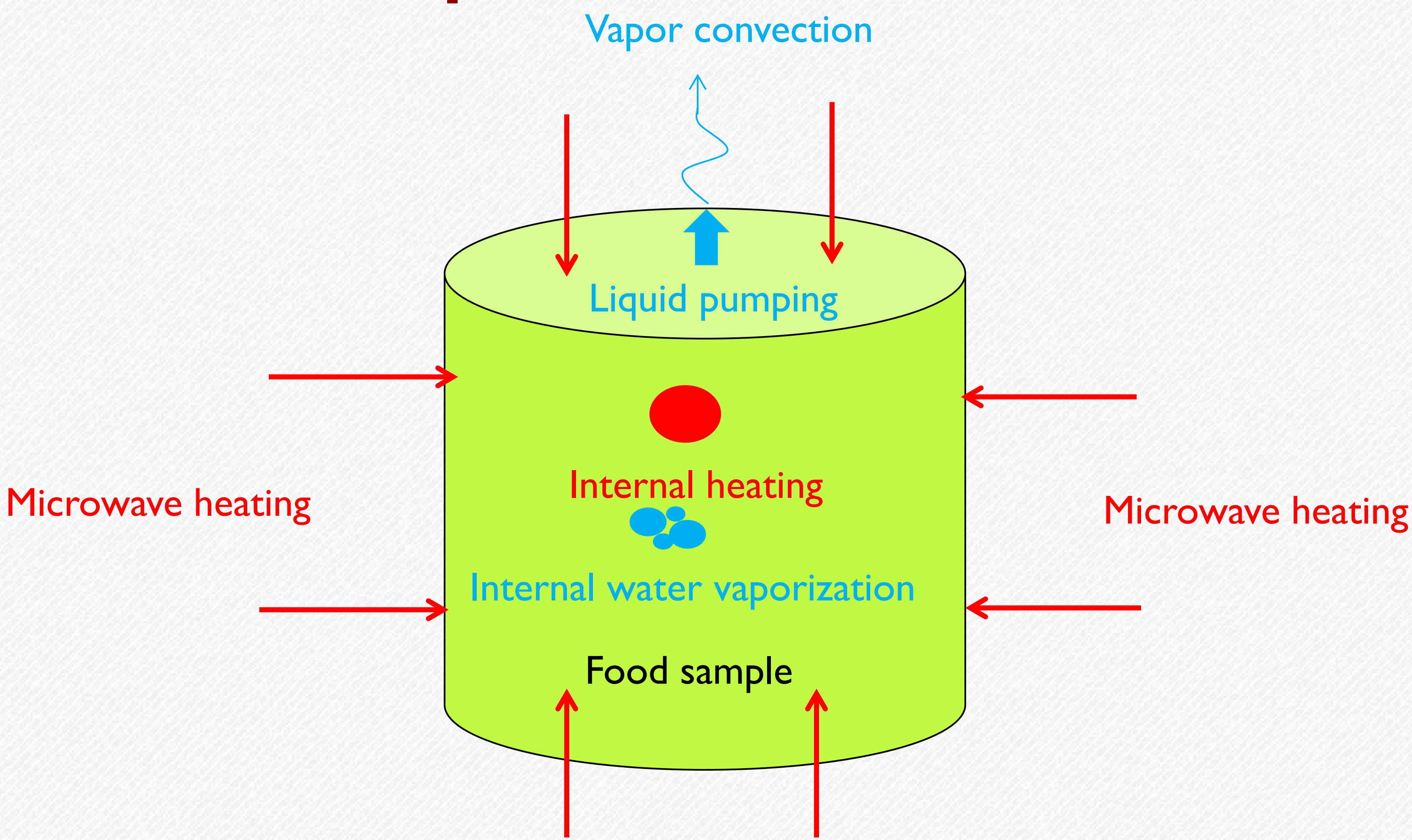
- Café steamer

Objectives

- Develop a comprehensive multiphysics model that includes:
  - Electromagnetic heating
  - Heat and mass transfer
  - Phase change of water evaporation
  - Laminar flow and heat transfer in headspace
- Evaluate the headspace steam on microwave heating performance

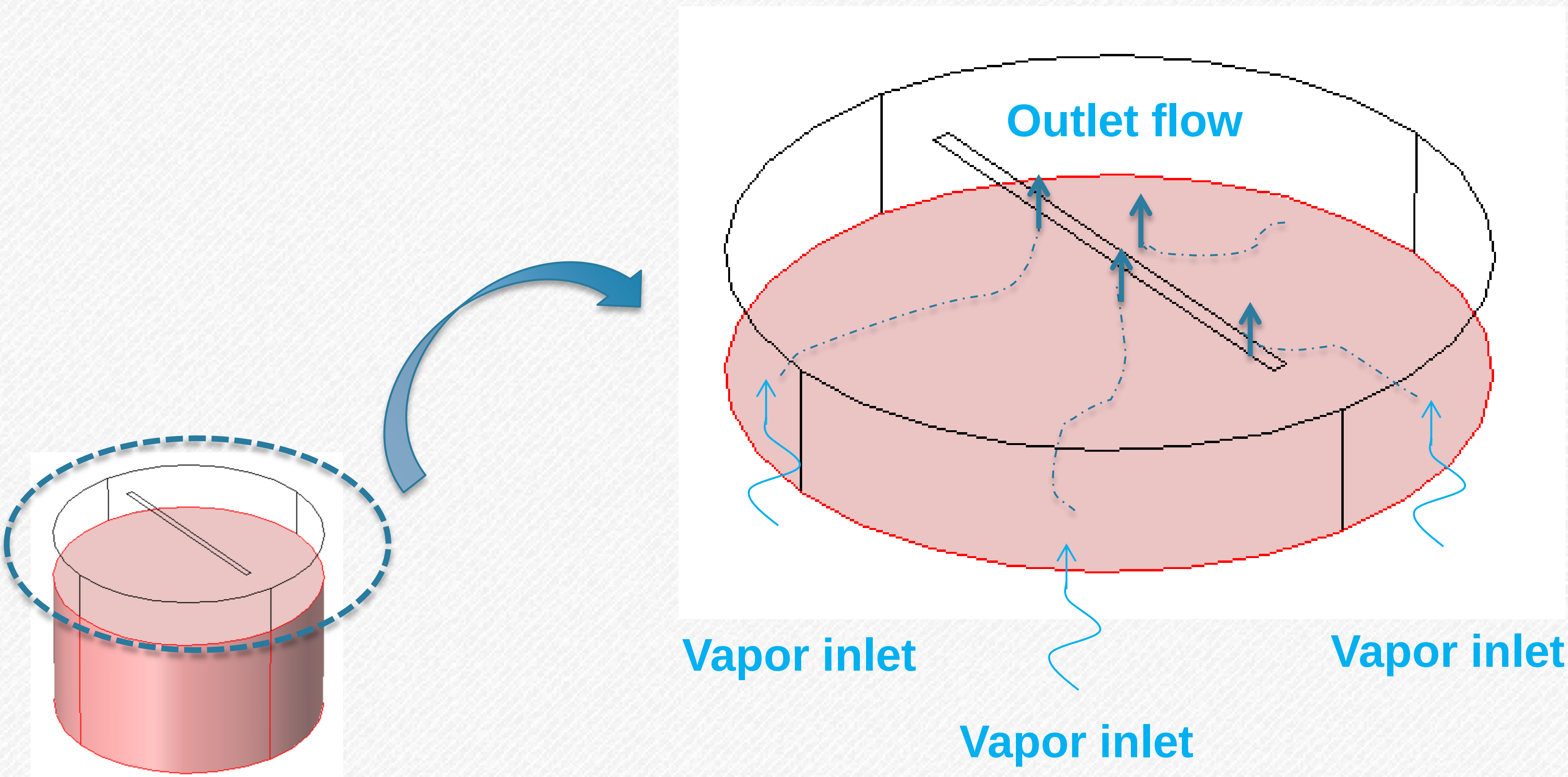
Model Development

Problem Description in Food Sample

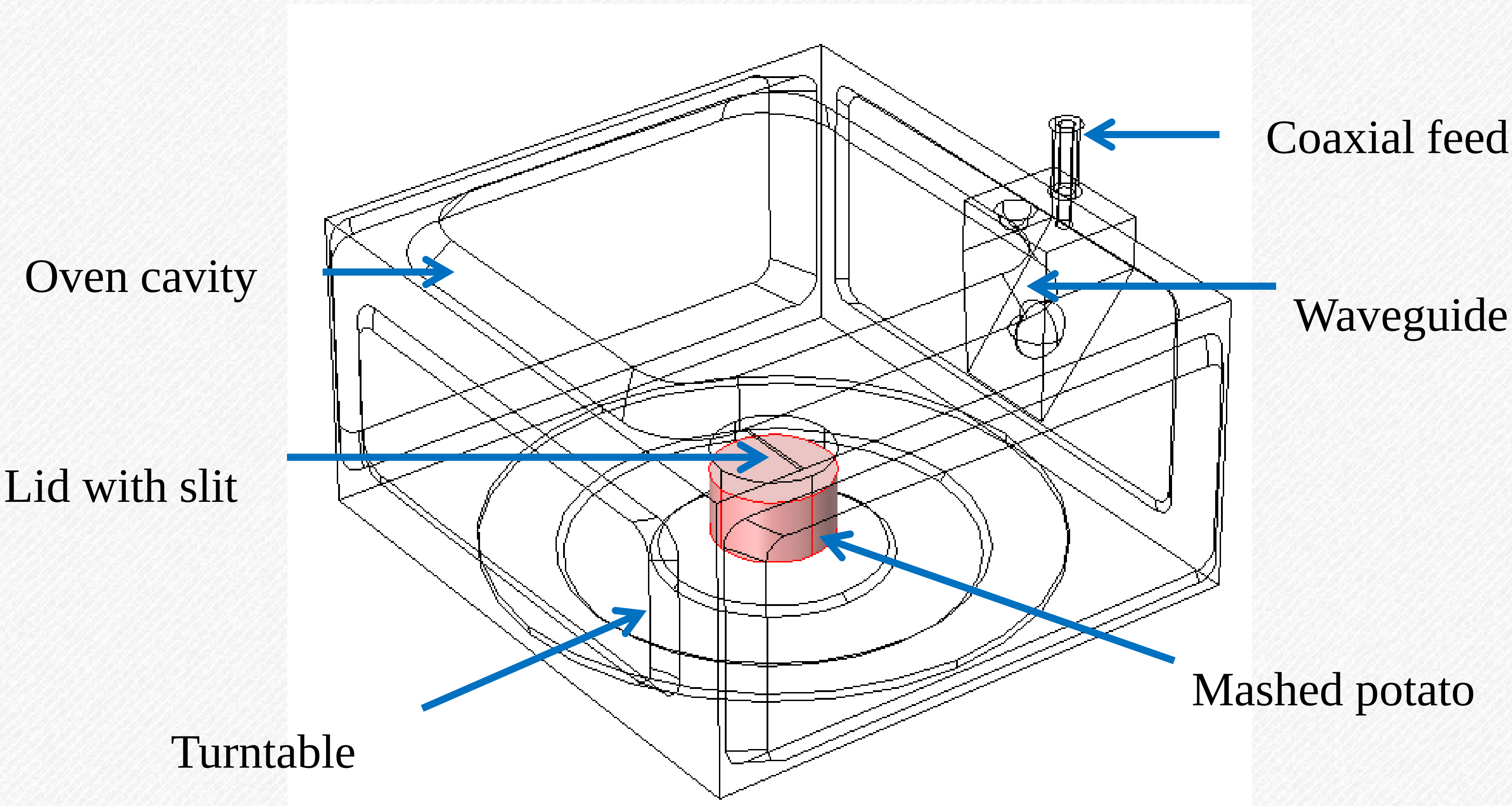


J. Chen, K. Pitchai, S. Birla, M. Negahban, D. Jones, J. Subbiah. 2014. Heat and mass transport during microwave heating of mashed potato in domestic oven – model development, validation, and sensitivity analysis. *Journal of Food Science*. DOI: 10.1111/1750-3841.12636.

Problem Description in Headspace



Geometric Model



Assumptions

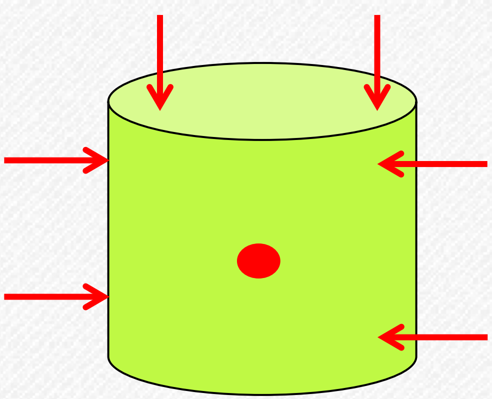
- Frequency 2.45 GHz
- Moisture condensation in headspace was ignored.
- The radiation from the hot steam to the food product was ignored.
- EM field and heat source was calculated using room temperature dielectric properties.

Governing Equations

Electromagnetics – Maxwell's Equations

$$\nabla \times \mu_r^{-1}(\nabla \times \mathbf{E}) - \left(\frac{2\pi f}{c}\right)^2 (\varepsilon_r - i\varepsilon'')\mathbf{E} = 0$$

$$Q = \pi f \varepsilon_0 \varepsilon'' \mathbf{E}^2$$



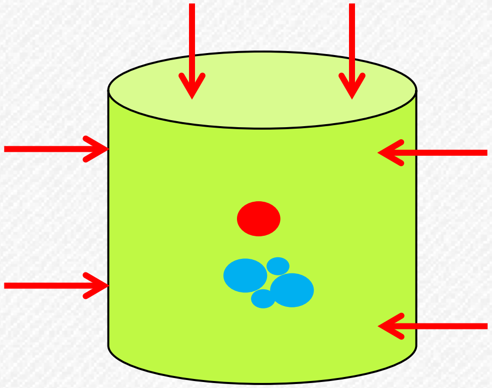
Food sample

f	Microwave frequency
c	Speed of light
ε_r	Dielectric constant
ε	Dielectric loss factor
μ_r	Permeability
Q	Power dissipation density

Governing Equations

Phase Change (Water Vaporization / Condensation)

$$I = \frac{K \cdot M_w \cdot (p_{v,eq} - p_v)}{R \cdot T}$$

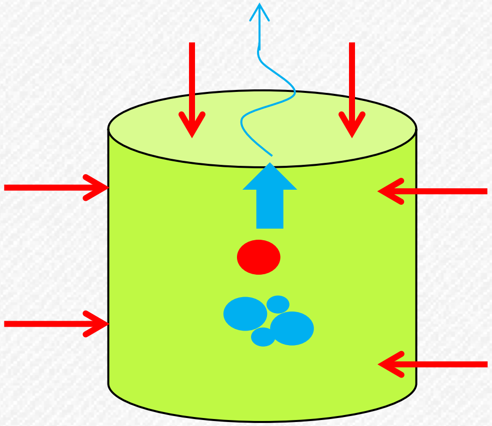


K	Evaporation rate constant
p_v	Vapor pressure
$p_{v,eq}$	Equilibrium water vapor pressure
R	Ideal gas constant
T	Temperature
M_w	Molecular weight of vapor/water

Governing Equations

Momentum Conservation – Darcy's Law

$$\mathbf{u_i} = -\frac{k_{in,i} \cdot k_{r,i}}{\mu_i} \nabla P$$



Food sample

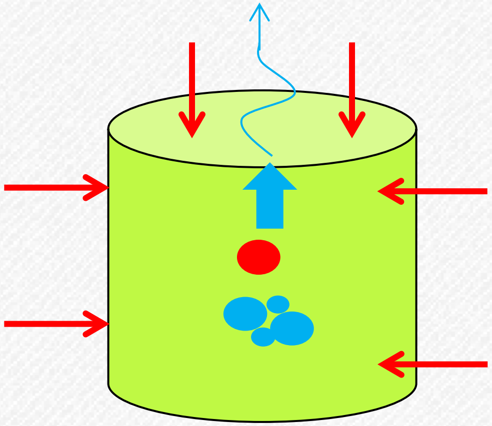
$\mathbf{u_i}$	Darcy's velocity,
$k_{in,i}$	Intrinsic permeability
$k_{r,i}$	Relative permeability
μ_i	Dynamic viscosity
P	Total pressure

Governing Equations

Mass Conservation

$$\frac{\partial c_i}{\partial t} + \nabla \cdot (-D_i \nabla c_i) + \mathbf{u} \cdot \nabla c_i = \pm I/Mw$$

Diffusion Convection Phase change



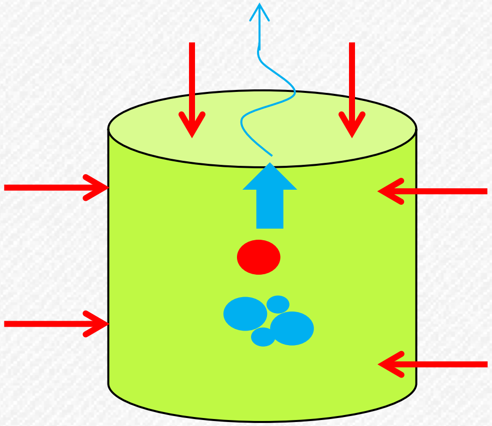
Food sample

c	Concentration of the species
D	Diffusion coefficient
I	Evaporation rate
u	Darcy's velocity

Governing Equations

Energy Conservation

$$\left(\rho C_p\right)_{eff}\frac{\partial T}{\partial t}+\rho C_p\mathbf{u}\cdot\nabla T=\nabla\cdot\left(k_{eff}\nabla T\right)-\lambda I+Q$$



Food sample

ρ	fluid density
C_p	fluid heat capacity
$\mathbf{u}$	fluid velocity field
$(\rho C_p)_{eff}$	effective heat capacity
k_{eff}	effective thermal conductivity
λ	latent heat of evaporation
I	evaporation rate
Q	heat source

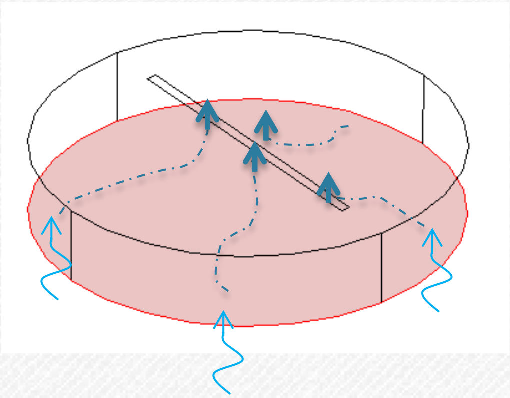
Governing Equations

Laminar flow of vapor

Navier-Stokes Equation

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{u}) = 0$$

$$\rho\frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u}\cdot\nabla)\mathbf{u} = \nabla\cdot\left[-p\mathbf{I} + \mu\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^{T}\right) - \frac{2}{3}\mu(\nabla\cdot\mathbf{u})\mathbf{I}\right] + \mathbf{F}$$



p Pressure

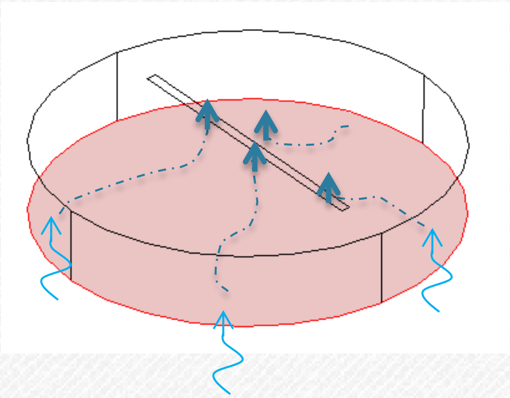
μ Viscosity

Governing Equations

Heat transfer of fluid

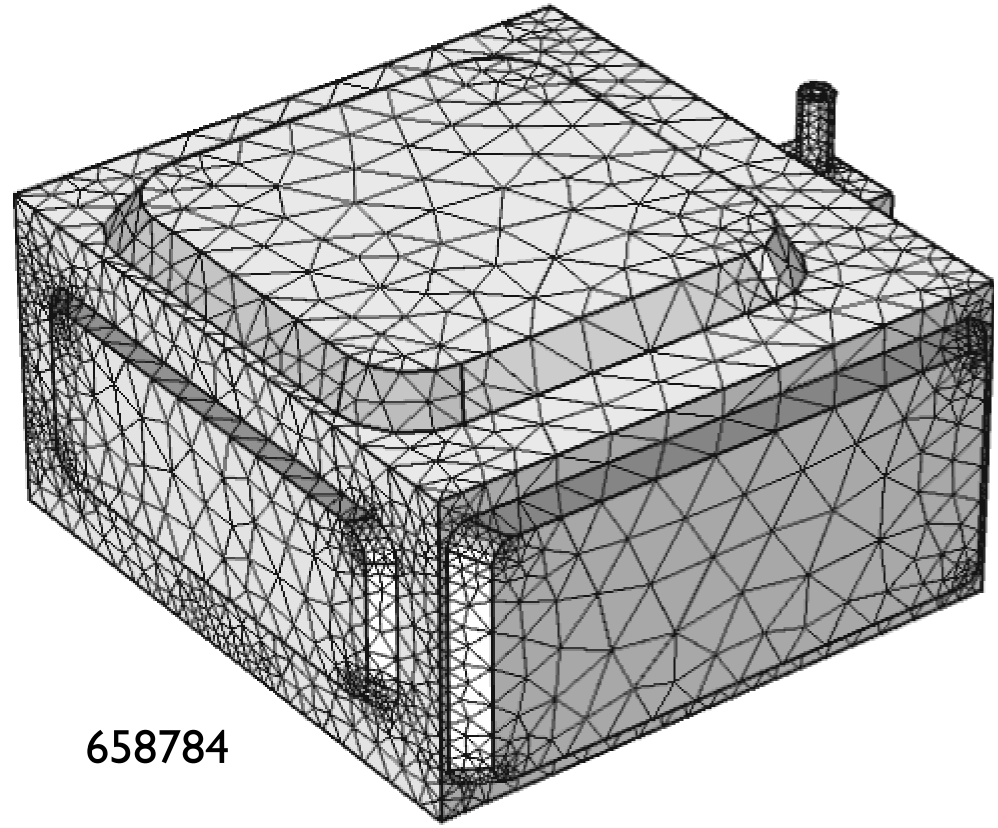
$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T)$$

ρ	Fluid density
C_p	Fluid heat capacity
$\mathbf{u}$	Fluid velocity field
K	Thermal conductivity
T	Temperature



Meshing

- Tetrahedral and prime elements



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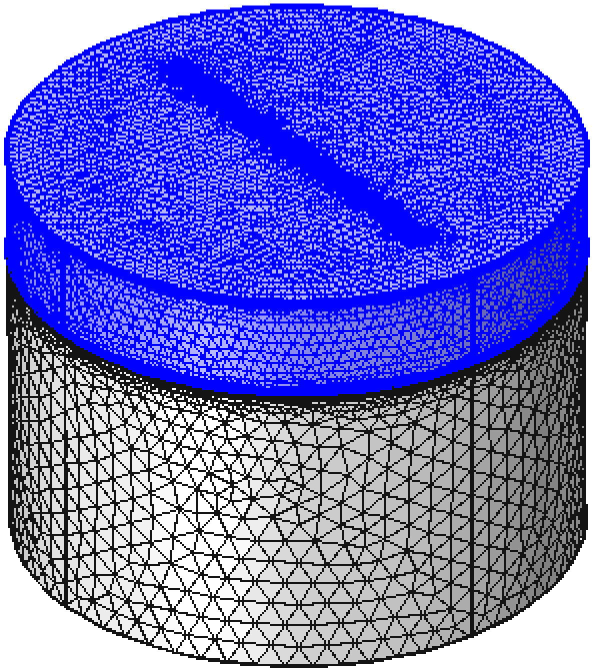

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Simulation Strategy

EM field
at 12 locations

↓

Averaged heat source

Heat from 4 °C for 90 s

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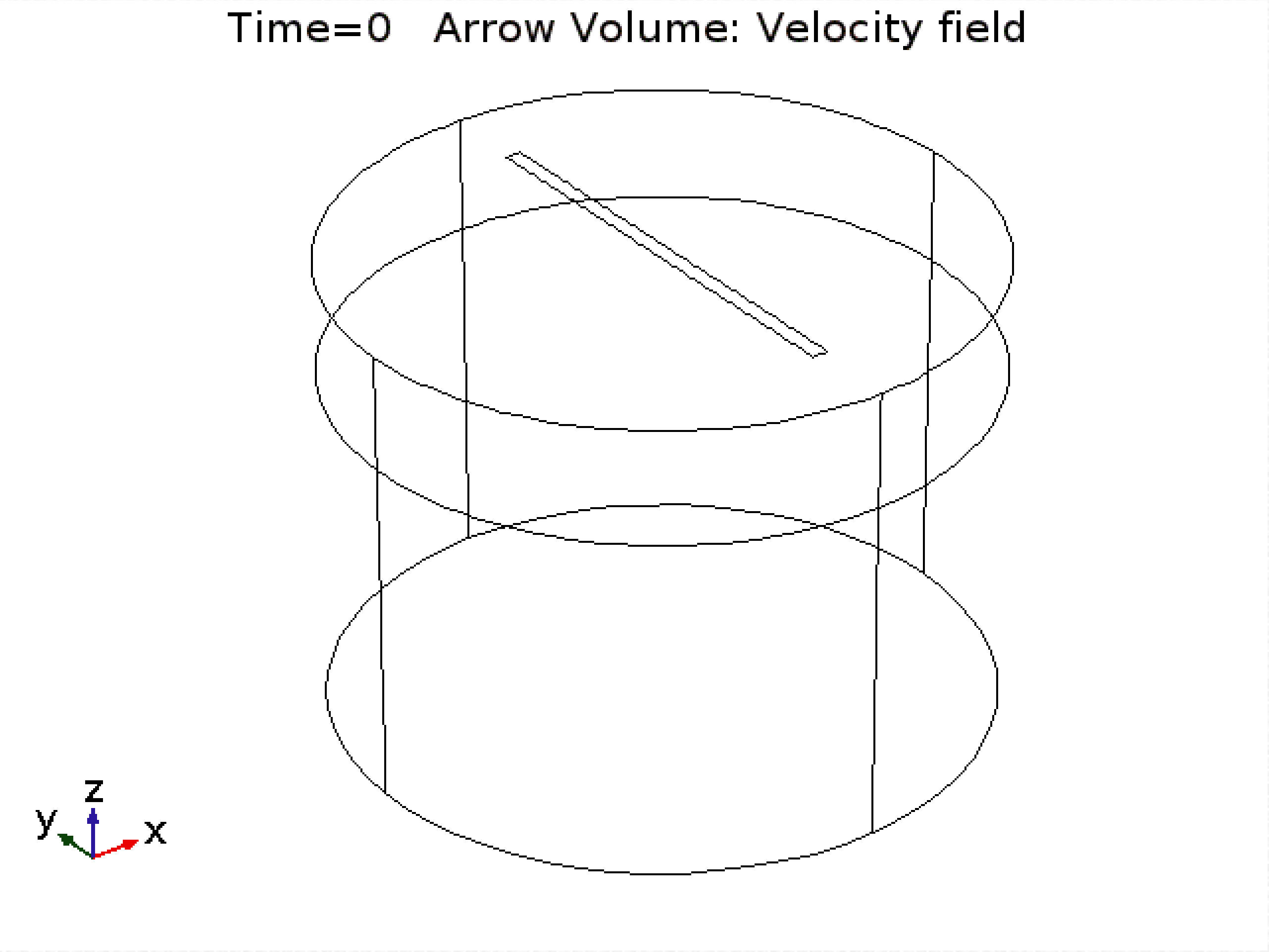
Laminar flow of vapor
Heat transfer in fluid of vapor

Heat and mass transfer
Phase change of water evaporation
Darcy's velocity

Fully coupled

Results and Discussion

Velocity in Headspace Animation



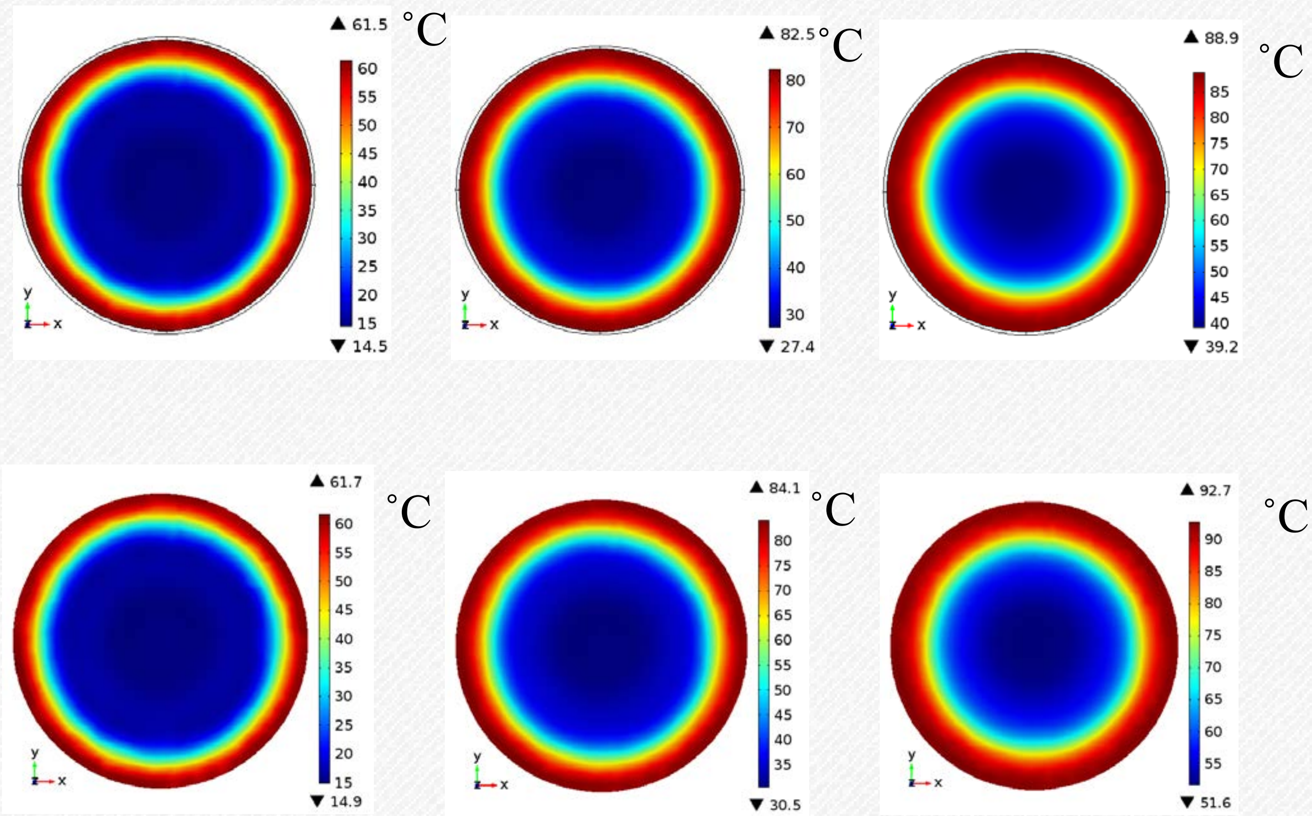
Spatial Temperature on Top Surface

- The headspace steam increased the temperature on the top surface

Time, s — 30 — 60 — 90

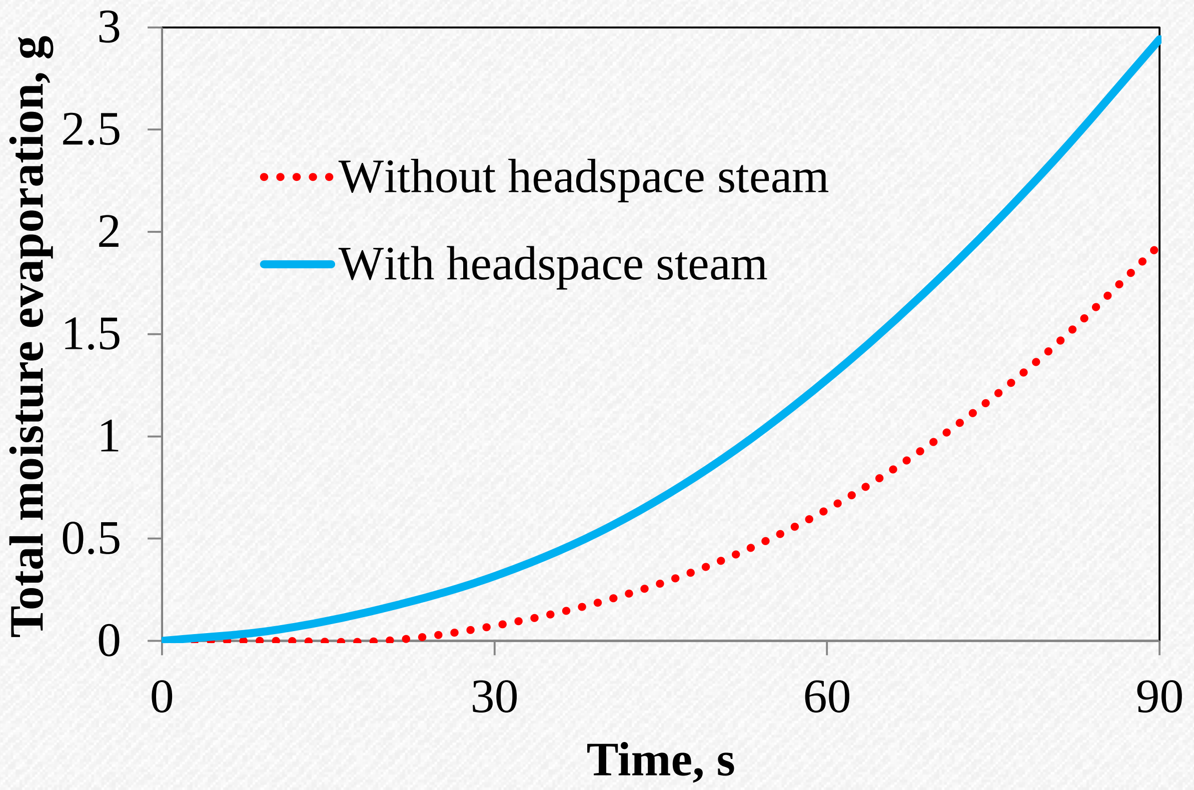
Without headspace

With headspace



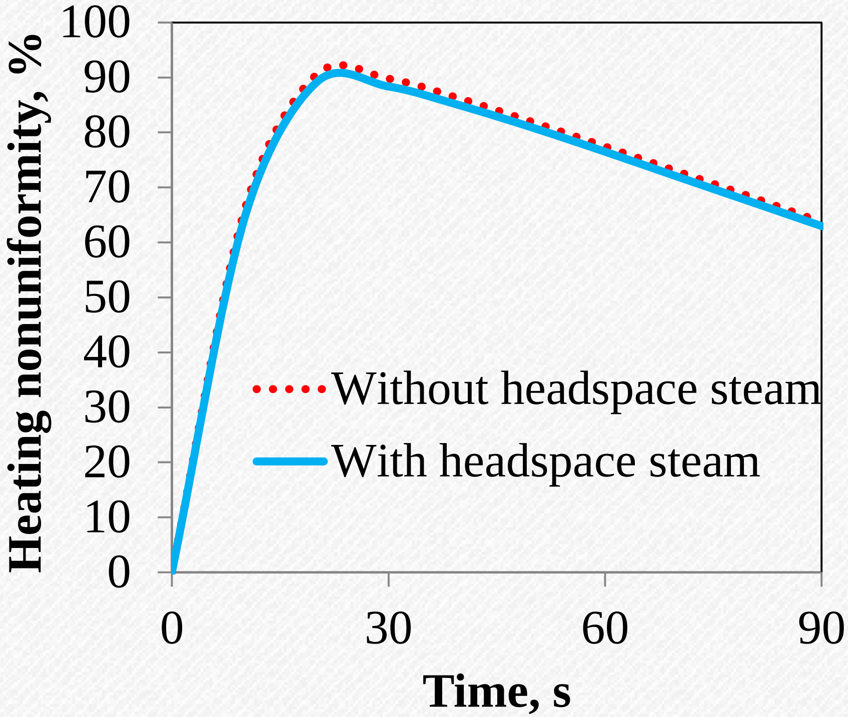
Total Moisture Evaporation

- The headspace steam increased the total moisture evaporation

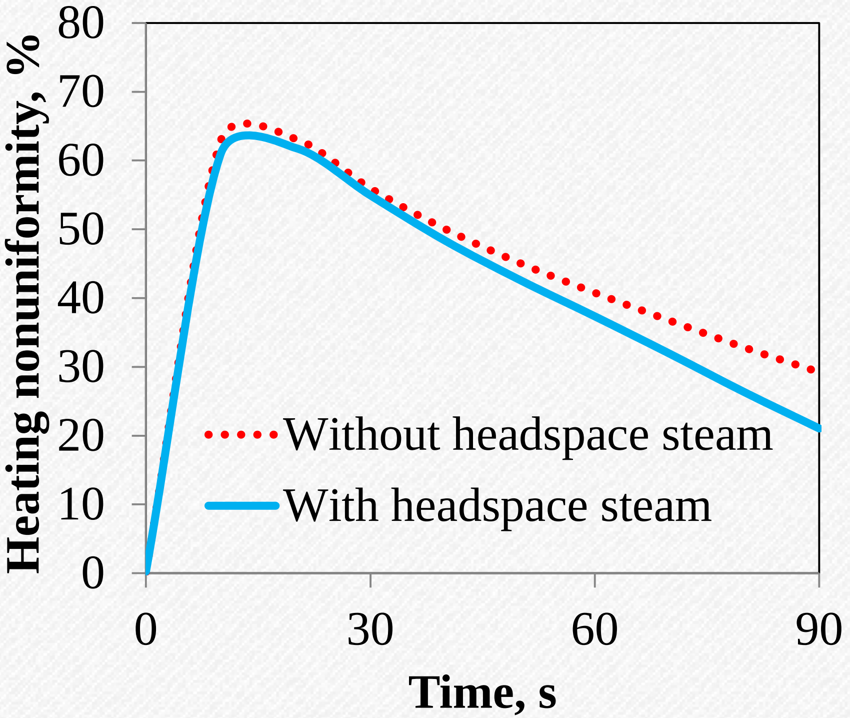


Heating Nonuniformity

- The headspace steam increased the heating uniformity on the top surface by 8%, but not for the whole food product.



Whole food product



Top surface

Standard deviation / average temperature

Conclusions

- A comprehensive model of microwave heating coupled with heat and mass transfer in food product and headspace was developed.
- The headspace steam increased the temperature on the top surface and the total moisture evaporation.
- The headspace steam increased the heating uniformity on the top surface by 8%, but not for the whole food product.
- The model needs to be further refined and validated before it can be used by the food industry to assist food development.

Thank you very much !

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