COMSOL CONFERENCE 2014 SHANGHAI

SCU

基于COMSOL的微波干燥优化

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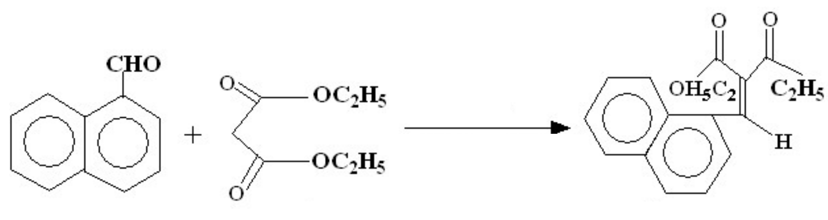
Outline

1. 微波能工业应用的机遇与挑战
2. 微波均匀干燥优化
3. 结论

微波对化学反应的高效作用

- 有机反应中重要的一类反应：缩合反应过程使用微波后节能效果非常明显，见下表。

α甲醛与丙二酸二乙酯的缩合反应

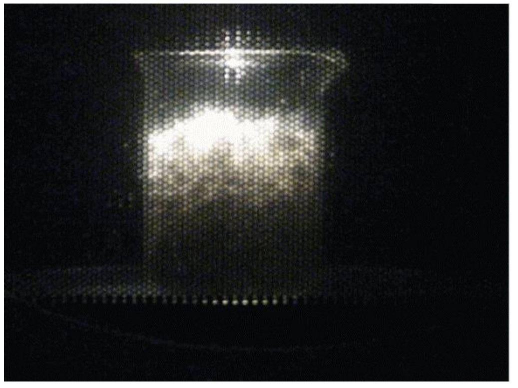


加热方式	耗时 （min）	收率 （%）	耗能 (KJ/mol)
传统加热	1440	44.7	4.9
微波加热	5	78	0.24

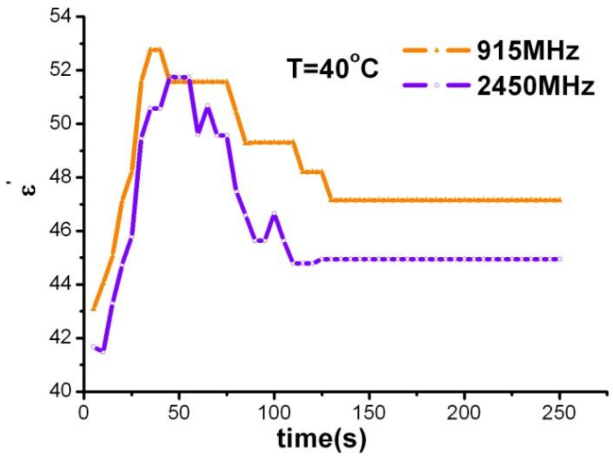
微波能工业应用的挑战

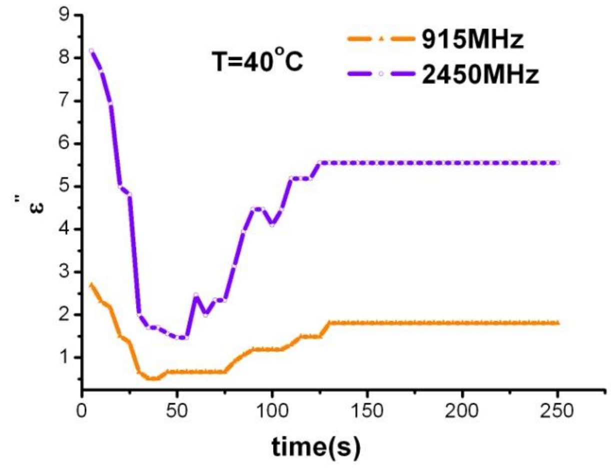
- 反应体系温度突变，导致反应物被烧毁或者爆炸。

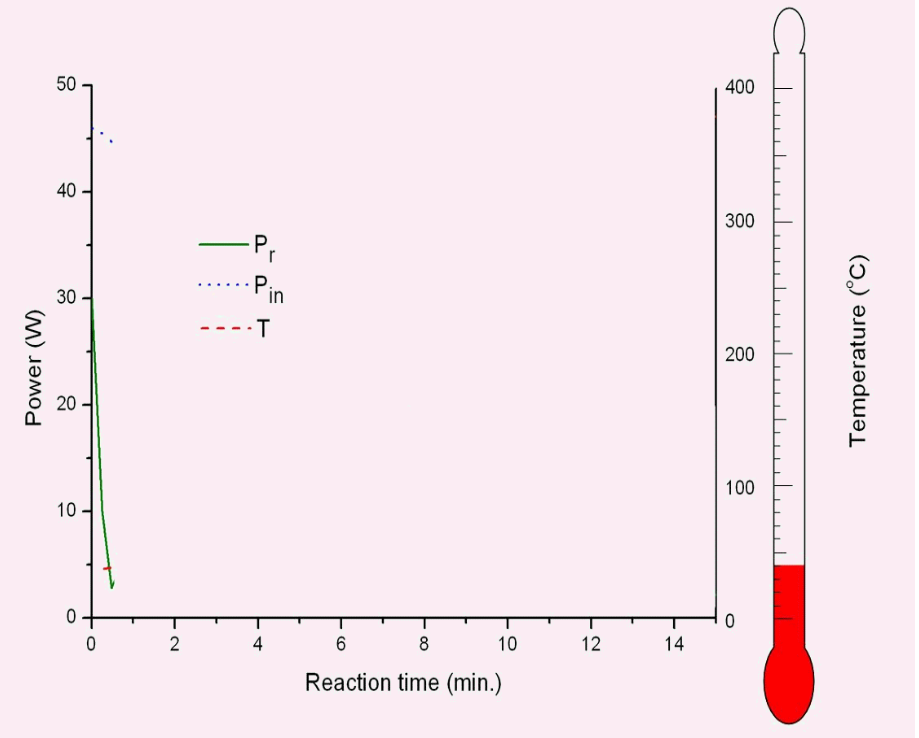
- 反应体系对微波能量反射突变，损坏微波源。



化学反应复介电系数的非线性特征

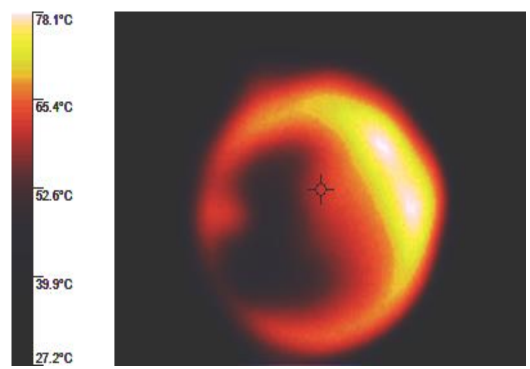






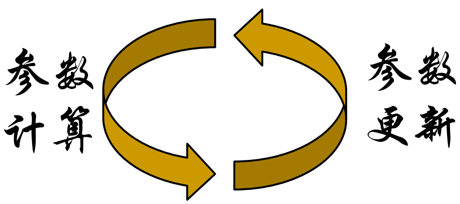
温度测量与反馈控制

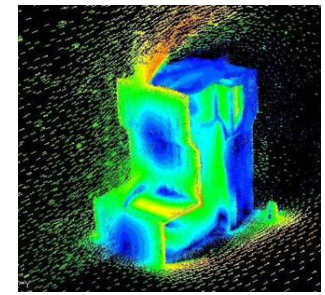
传统的温度测量与反馈控制



反应体系中温度分布不均匀

基于多物理场的优化与预测





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- Maxwell's equations:

$$\nabla \times \mathbf{E} = -j\omega\mu\mathbf{H}$$

$$\nabla \times \mathbf{H} = j\omega\varepsilon\varepsilon_0\mathbf{E}$$

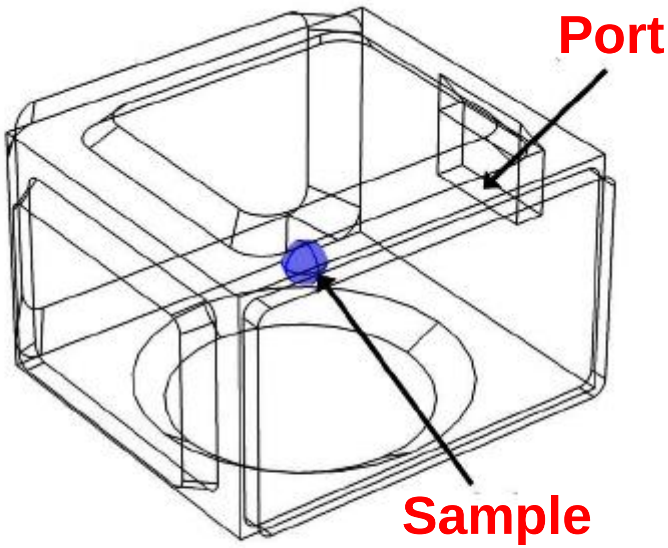
$$\nabla \cdot (\varepsilon\mathbf{E}) = 0$$

$$\nabla \cdot \mathbf{H} = 0$$

E= Electric field intensity

H= Magnetic field intensity

ω= Angular Frequency



Microwave oven geometry

Relative permittivity:

$$\varepsilon = \underbrace{\varepsilon'(M,T)}_{\text{dielectric constant}} - j\overbrace{\varepsilon''(M,T)}^{\text{dielectric loss}}$$

- Power absorbed (by the sample): $Q_{mic} = \frac{1}{2}\omega\varepsilon_0\varepsilon''|\mathbf{E}|^2$

多孔介质中的传输过程

Momentum Conservation

Darcy's Law

$$\frac{\partial c_g}{\partial t} + \nabla \cdot \left(\mathbf{n}_{\mathbf{g,G}}\right) = \dot{I}$$

$$\mathbf{n}_{\mathbf{g,s}} = -\rho_g \frac{k_g k_{r,g}}{\mu_g} \nabla P$$

$$\mathbf{v}_{\mathbf{i}} = \underbrace{-\frac{k_i k_{r,i}}{\mu_i} \nabla P}_{\text{Darcy Velocity}}$$

i = water, gas

Mass Conservation

Liquid Water

$$\frac{\partial c_w}{\partial t} + \underbrace{\nabla \cdot \left(\rho_w \mathbf{v}_{\mathbf{w}}\right)}_{\text{bulk flow}} = \underbrace{\nabla \cdot \left(D_w \nabla c_w\right)}_{\text{capillary flow}} - \overbrace{\dot{I}}^{\text{phase change}}$$

Water Vapor

$$\frac{\partial c_v}{\partial t} + \underbrace{\nabla \cdot \left(\rho_g \omega_v \mathbf{v}_{\mathbf{g}}\right)}_{\text{bulk flow}} = \underbrace{\nabla \cdot \left(\varphi S_g \frac{C^2}{\rho_g} M_a M_v D_{eff,g} \nabla x_v\right)}_{\text{binary diffusion}} + \overbrace{\dot{I}}^{\text{phase change}}$$

Energy Conservation

Thermal Balance for Mixture

$$\frac{\partial}{\partial t}\left[\sum_{i=s,w,v,a}\left(c_i c_{p,i} T\right)\right] + \underbrace{\nabla \cdot \left[\sum_{i=w,v,a}\left(c_{p,i} \mathbf{n}_{\mathbf{i}} T\right)\right]}_{\text{convection}} = \underbrace{\nabla\left(k_{eff} \nabla T\right)}_{\text{conduction}} - \overbrace{\lambda \dot{I}}^{\text{phase change}} + \underbrace{Q_{mic}}_{\text{microwave source}}$$

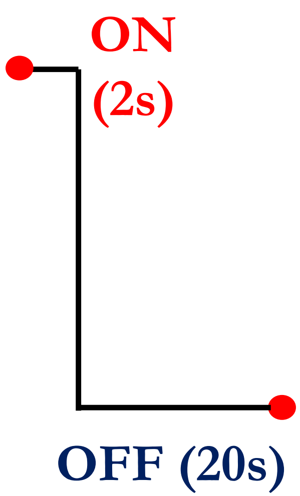
Phase Change

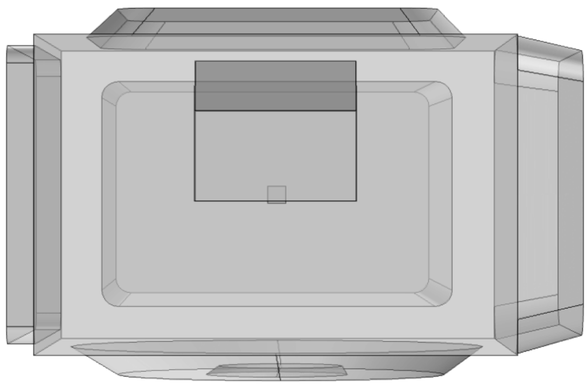
Evaporation-Condensation

$$\dot{I} = K \frac{M_v}{RT} \underbrace{\left(p_{v,eq} - p_v\right)}_{\text{Non-Equilibrium Formulation}}$$

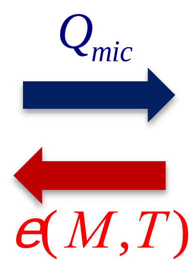
3D coupled Electromagnetics + Heat and Mass Transport Model with Pressure Driven flow

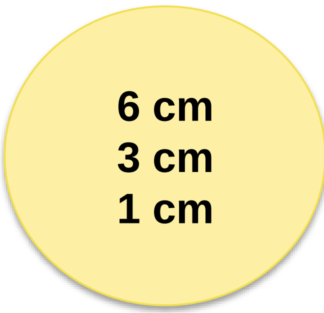
- Microwave drying of potatoes carried out at 10% Power Level for 10 min.





Electromagnetics in microwave oven





Multiphase transport in porous media

Process Parameters of Interest

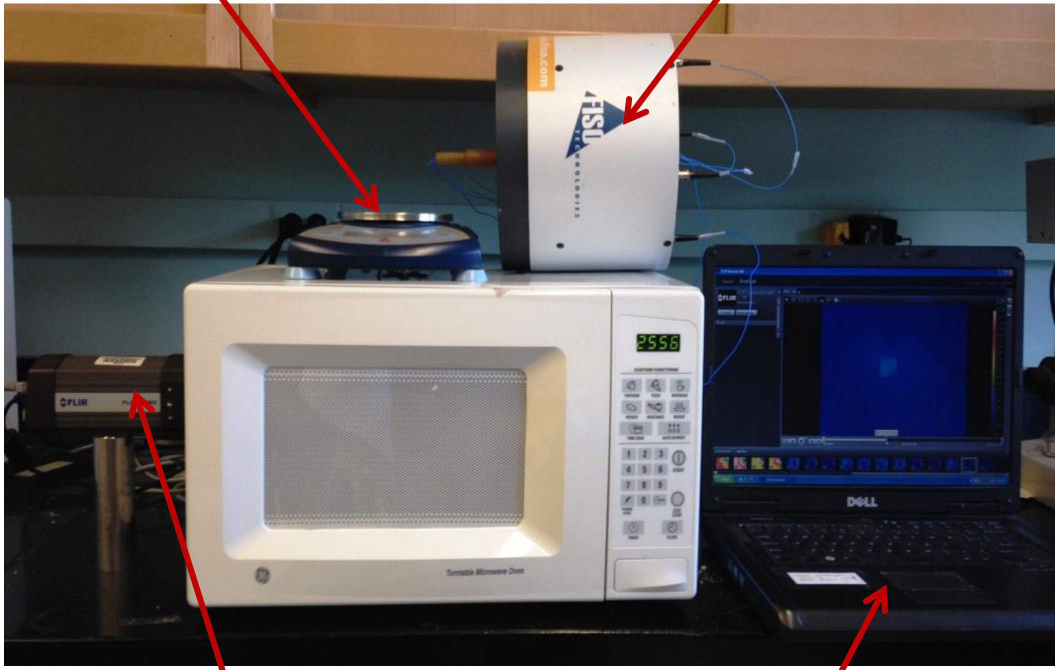
Moisture loss	Heating concentration	Pressure development	Drying uniformity

实验设置

Temperature, Pressure and Moisture Measurements

Digital weighing balance

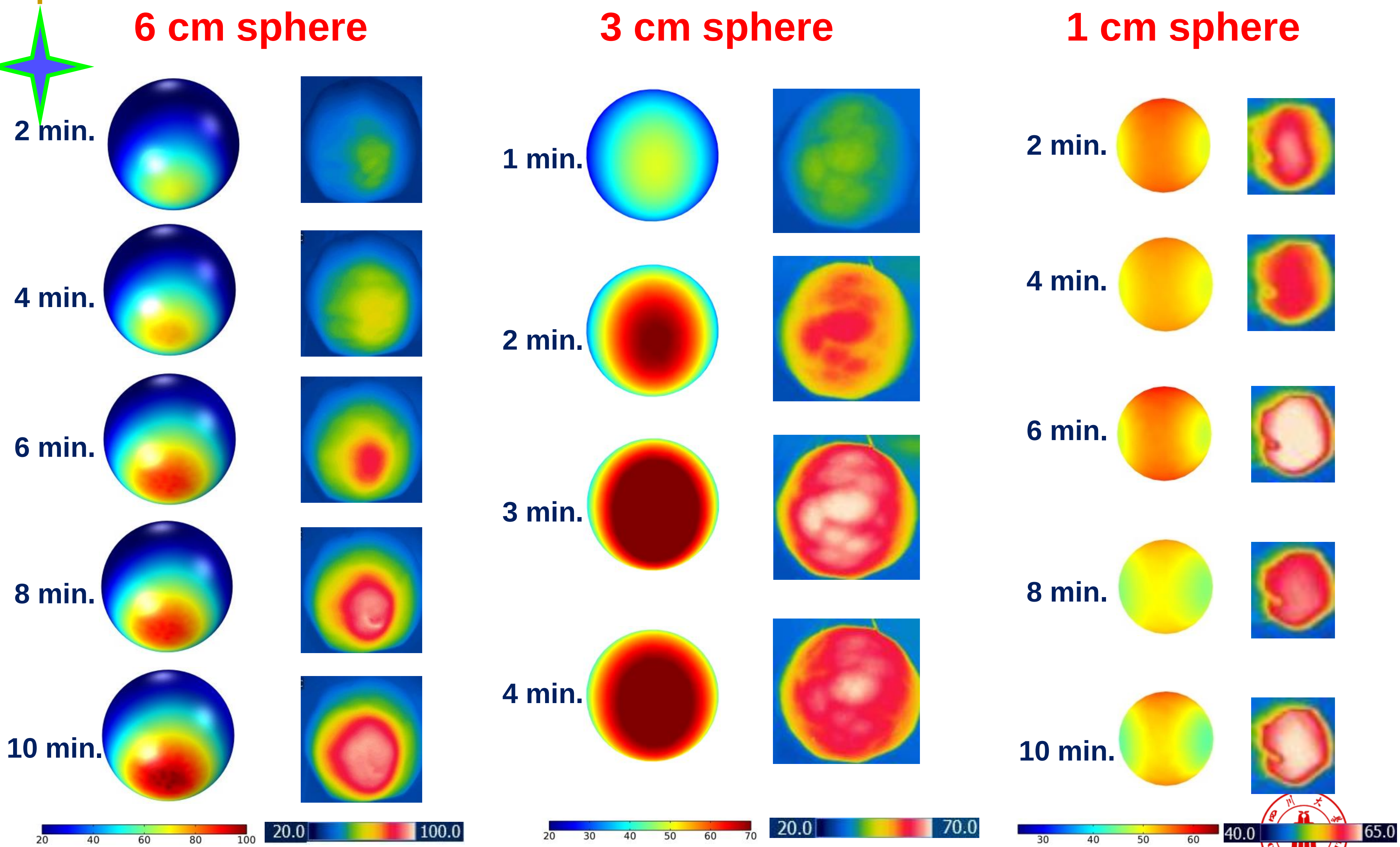
Fiber optic sensors



Infrared camera

Data acquisition system

表面温度分布

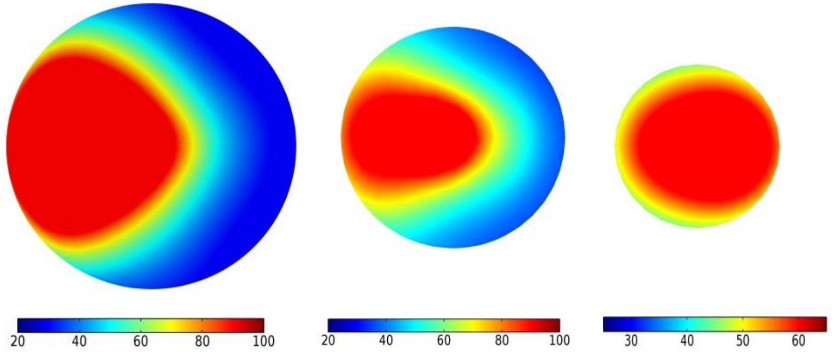


6 cm sphere
3 cm sphere
1 cm sphere
2 min.
4 min.
6 min.
8 min.
10 min.
1 min.
2 min.
3 min.
4 min.
2 min.
4 min.
6 min.
8 min.
10 min.
20 40 60 80 100
20.0 100.0
20 30 40 50 60 70
20.0 70.0
30 40 50 60
40.0 65.0

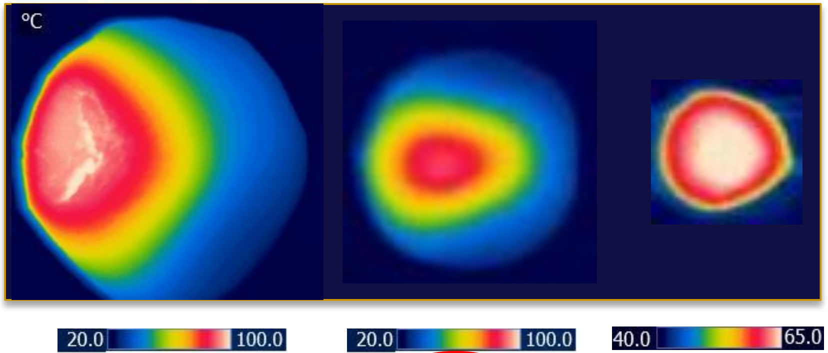
电磁聚焦和压力分布

SIMULATED

6 cm sample 3 cm sample 1 cm sample



ACTUAL

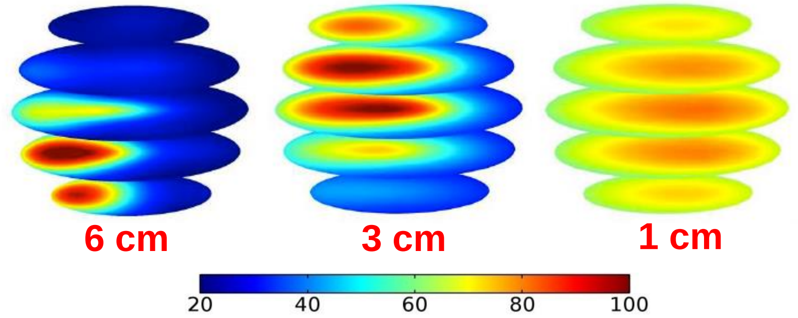


10 min. 2 min. 10 min.

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

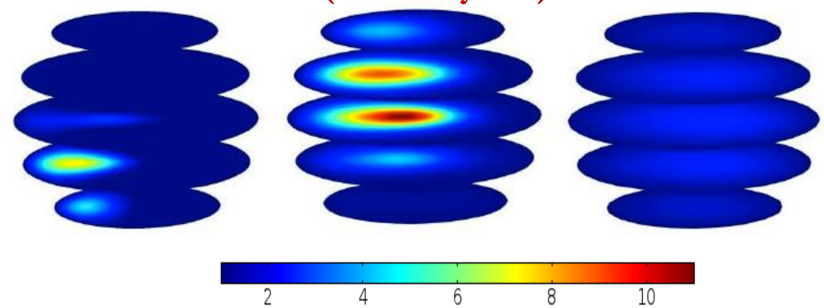
Simulated Temperature Distribution

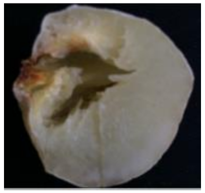
(after 8 cycles)



Simulated Pressure Distribution

(after 8 cycles)

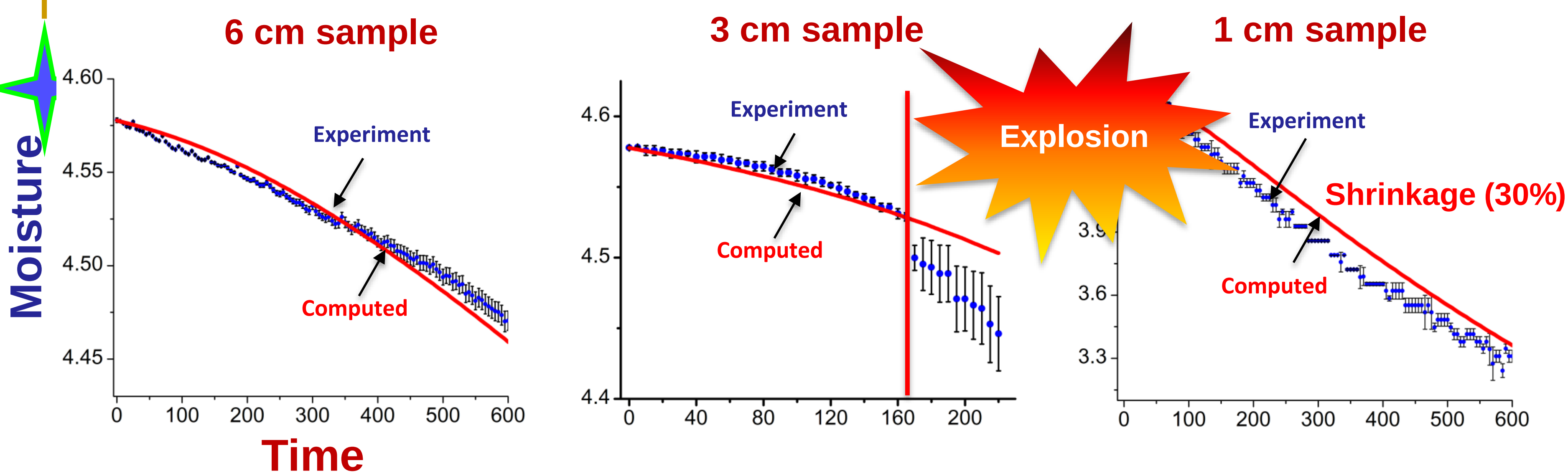




3 cm

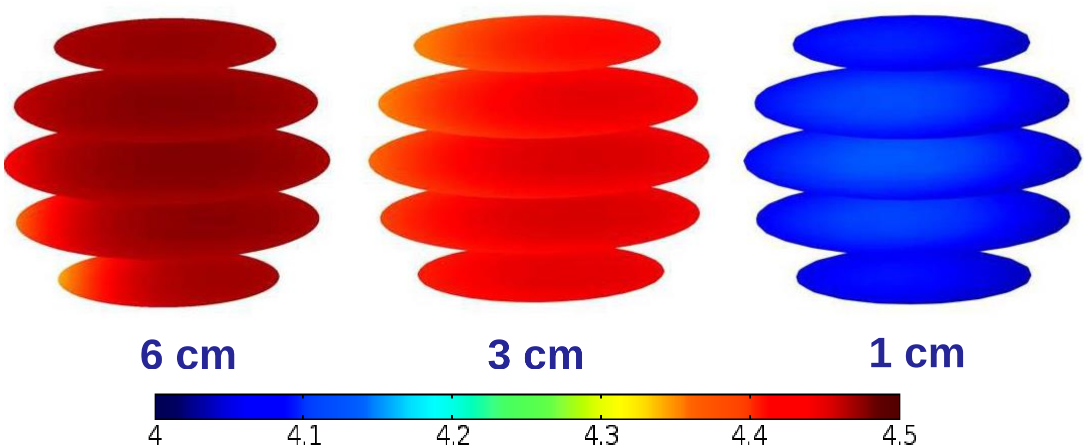
Stress inside (1.35 MPa) > Failure Stress (1.1 MPa)

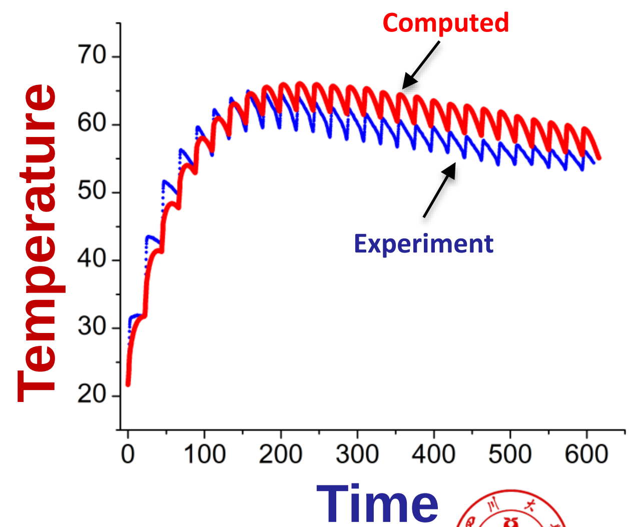
水分含量



Simulated Moisture Distribution

(after 8 cycles)





总结

- 电磁场和多相多孔介质的模型耦合完成微波干燥过程的多物理场计算模型
- 小尺寸的球形土豆更合适微波干燥，原因如下：

1）相对均匀的温度分布，中心和边缘的温差低于15℃；
2）较低且较均匀的内部压力水平，有利于质量的提高；
3）10%微波功率水平的微波加热最高温度不超过80℃，属于低温干燥，干燥质量相比于高温干燥更高。

- 最后从多物理计算角度分析了腔体内温度、微波功率、风速对干燥结果的影响，进一步分析获得了较优的干燥方案。

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Thank you for your attention