Modeling Dielectric Heating: A First Principles Approach

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COMSOL CONFERENCE
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Introduction

What are the Two Types of Electromagnetic Heating?

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1. Joule Heating

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1. **Joule Heating**

2. **Dielectric Heating**

How are the Two Types of Electromagnetic Heating Different?

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1. Joule Heating

Based on Ohm's Law

How are the Two Types of Electromagnetic Heating Different?

1. Joule Heating

Based on Ohm's Law Applied over time = Joule's First Law

$$Power\,(\text{Watts/second}) = I(\text{current}) * V(\text{voltage}) = I^2(\text{current}^2) * R(\text{resistance}) = \frac{V^2(\text{voltage}^2)}{R(\text{resistance})}$$

How are the Two Types of Electromagnetic Heating Different?

1. Joule Heating

Based on Ohm's Law
Applied over time =
Joule's First Law

Mechanism: Charged Free Carrier Flow
Electrons, Electrons and/or Ions

How are the Two Types of Electromagnetic Heating Different?

2. Dielectric Heating

Non-Ohmic Heating
Mechanism

How are the Two Types of Electromagnetic Heating Different?

2. Dielectric Heating

Non-Ohmic Heating Mechanism

First discovered and patented at Bell Telephone Laboratories in 1937 by Joseph G. Chaffee

How are the Two Types of Electromagnetic Heating Different?

2. Dielectric Heating

Non-Ohmic Heating Mechanism

Dielectric Heating typically occurs in the absence of free carriers in nominally non-conductive materials (dielectrics).

How are the Two Types of Electromagnetic Heating Different?

2. Dielectric Heating

Non-Ohmic Heating Mechanism

Dielectric Heating occurs as a result of the relative motion of bound electrons, ions, atoms, and molecules, in situ.

How are the Two Types of Electromagnetic Heating Different?

2. Dielectric Heating

Non-Ohmic Heating Mechanism

During electromagnetic excitation, the relative motion (vibration) of the bound electrons, ions, atoms, and molecules, in situ, couple to the bulk of the material. These vibrations are known as heat.

How are the Two Types of Electromagnetic Heating Different?

2. Dielectric Heating

Non-Ohmic Heating Mechanism

Different materials have a different relative permittivity (dielectric constant). The permittivity of Free Space is:

ε_0 = permittivity of Free Space

c_0 = speed of light

μ_0 = permeability of Free Space

$$\varepsilon_0 = \frac{1}{c_0 \mu_0} = 8.85419\, x\, 10^{-12} [F/m]$$

How are the Two Types of Electromagnetic Heating Different?

2. Dielectric Heating

Non-Ohmic Heating Mechanism

$$\varepsilon = \varepsilon_r \varepsilon_0$$

$where:$

ε_r = relative permittivity

ε_0 = permittivity of Free Space

How are the Two Types of Electromagnetic Heating Different?

2. Dielectric Heating

Non-Ohmic Heating Mechanism

For very complicated materials with phase delays and energy losses

$$\hat{\varepsilon} = \varepsilon'(\omega) + i\varepsilon''(\omega)$$

where :

$\varepsilon'(\omega) = \text{real part}$

$\varepsilon''(\omega) = \text{imaginary part}$

$\omega = 2 * \pi * f_0$ and $f_0 = \text{frequency}$

How are the Two Types of Electromagnetic Heating Different?

2. Dielectric Heating

Non-Ohmic Heating Mechanism

For very complicated materials with phase delays and energy losses

The loss equation is:

$$Q_d = 2 * \pi * f_0 * \varepsilon'' * \varepsilon_0 * \left(\frac{V_{in}}{thickness}\right)$$

$$where: f_0 = \text{frequency}$$

Dielectric Heating Model Materials

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whey gel = water + impurities (~10%)

formed into a gelatinous mass

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whey gel = water + impurities (~10%)

formed into a gelatinous mass

Frequency (measured)	Real Part (measured)	Imaginary Part (measured)
27 MHz	96.30	1879.15
40 MHz	83.95	1263.20
915 MHz	54.20	61.30
1800 MHz	51.70	34.57

After: Yifen Wang, et.al., J. Food Eng., 57 (2003), pp. 257-268

Dielectric Heating Model Materials

Real Part Fit Equation

$$\varepsilon' = 54.6919 - 2.05493x10^{-9} * f_0 + 1.27475x10^{9} * f_0^{-1} - 4.04542x10^{15} * f_0^{-2}$$

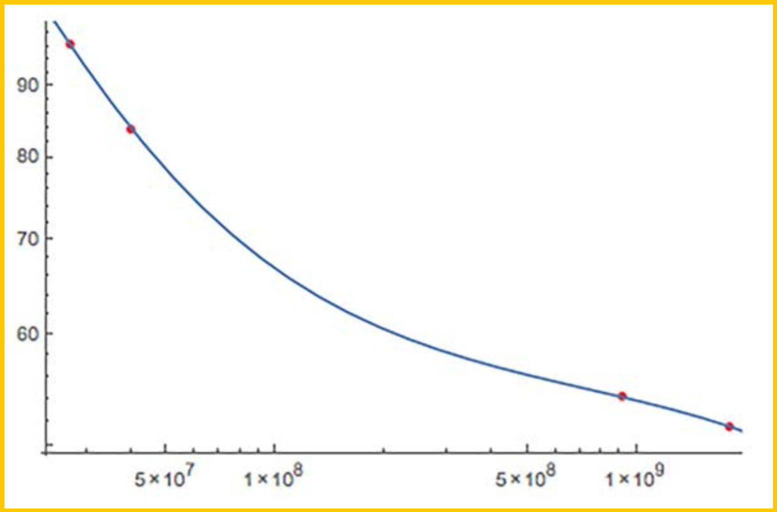
$f_0 =$ frequency

Imaginary Part Fit Equation

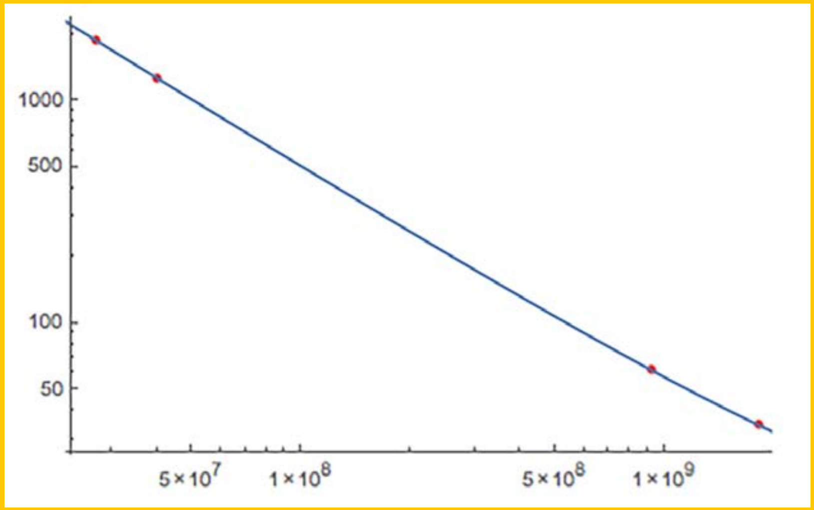
$$\varepsilon'' = 6.88131 + 1.59761x10^{-10} * f_0 + 4.96322x10^{10} * f_0^{-1} + 2.48106x10^{16} * f_0^{-2}$$

Dielectric Heating Model Materials

Combined Real Part



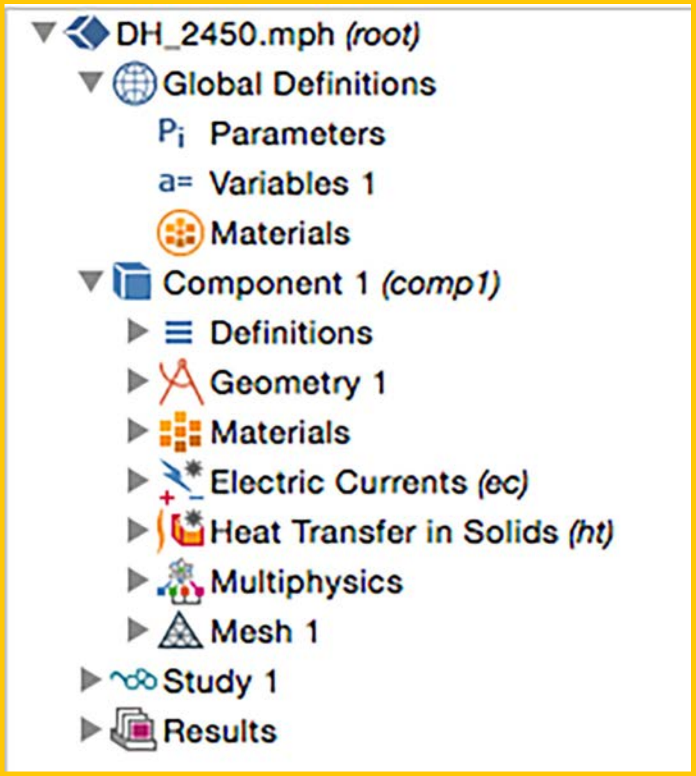
Combined Imaginary Part



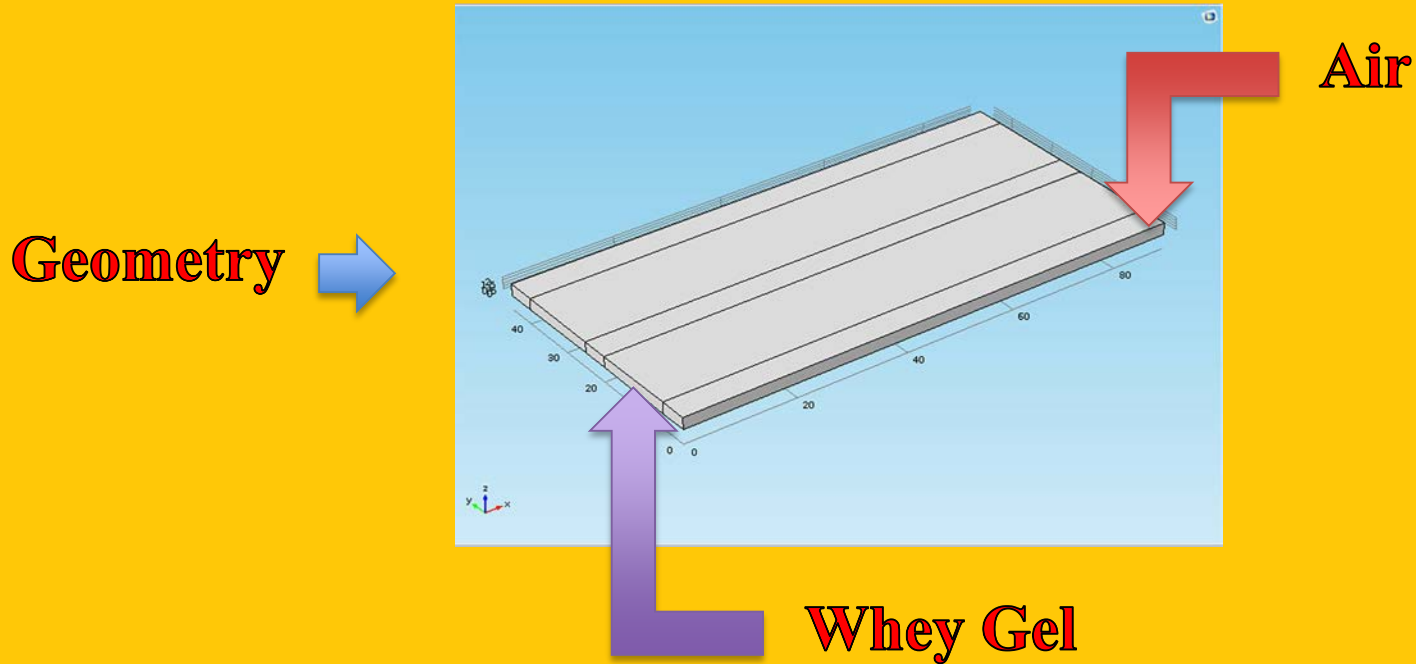
Data and Fit Plots

Dielectric Heating: COMSOL Multiphysics Model

Model Builder Tree

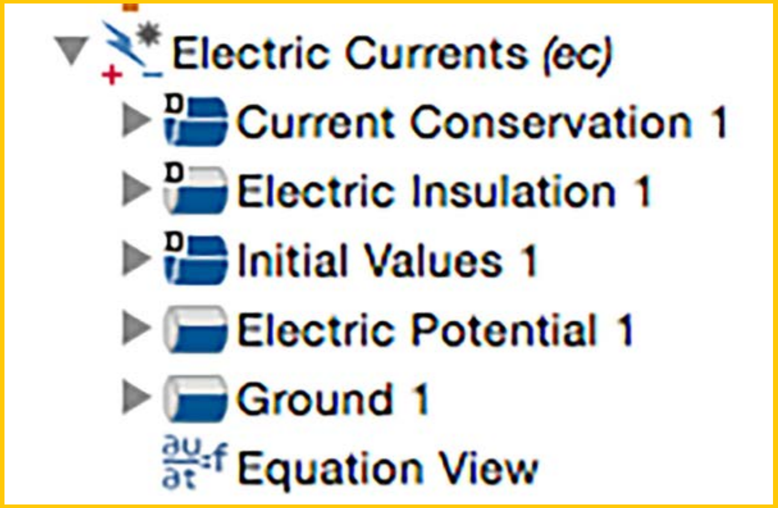


Dielectric Heating: COMSOL Multiphysics Model



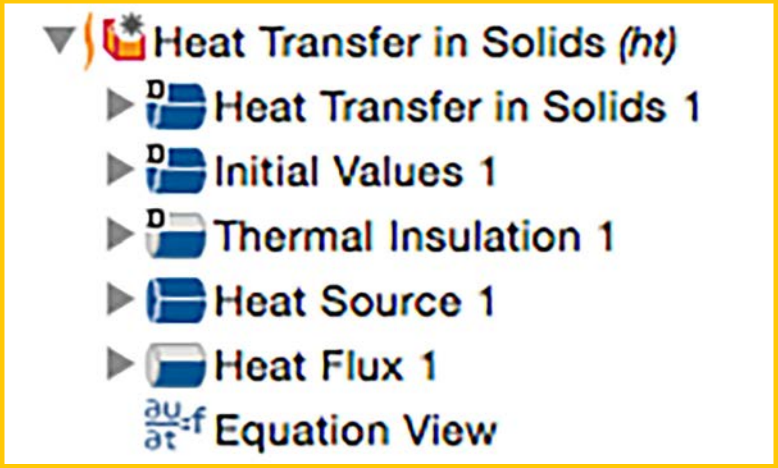
Dielectric Heating: COMSOL Multiphysics Model

Electric Currents



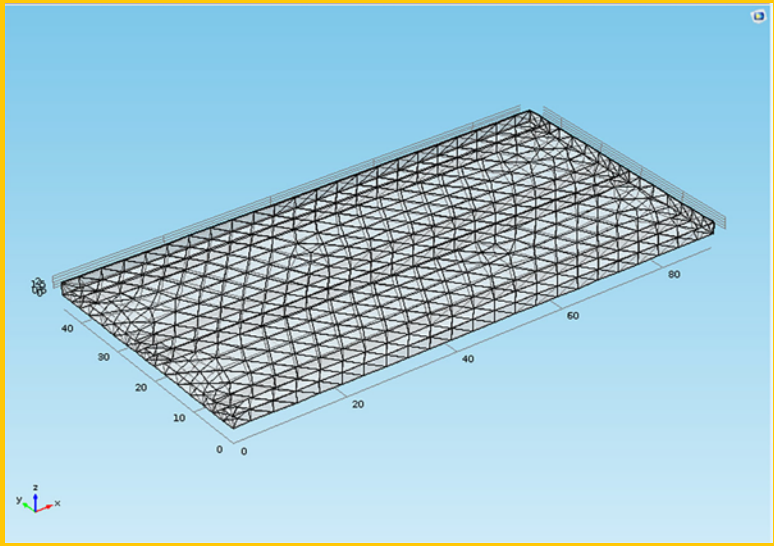
Dielectric Heating: COMSOL Multiphysics Model

Heat Transfer



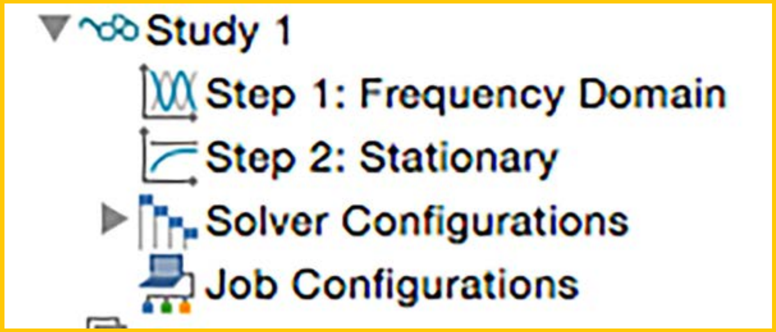
Dielectric Heating: Solving the COMSOL Multiphysics Model

Model Mesh



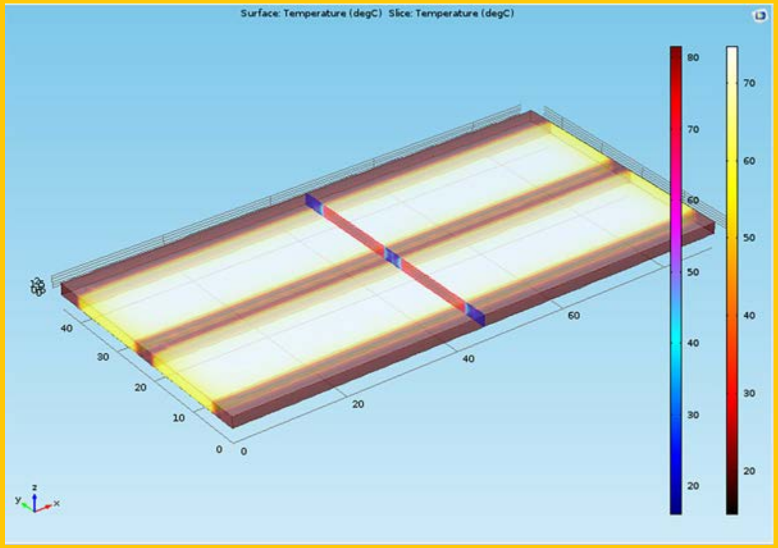
Dielectric Heating: Solving the COMSOL Multiphysics Model

Solver Configuration



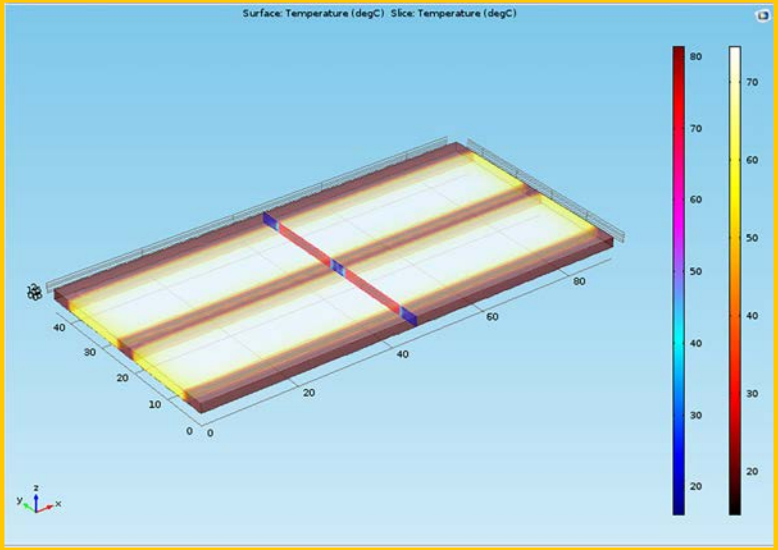
Dielectric Heating: Solutions to the COMSOL Multiphysics Model

Solution
2.45 GHz



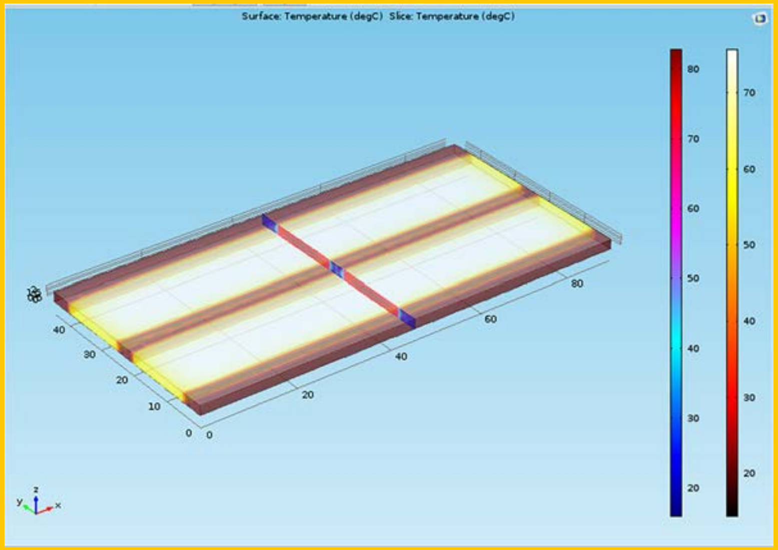
Dielectric Heating: Solutions to the COMSOL Multiphysics Model

Solution
915 MHz



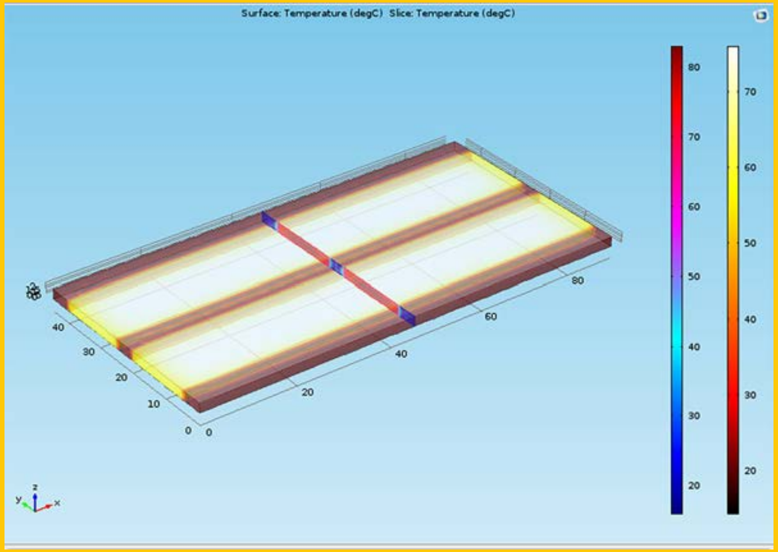
Dielectric Heating: Solutions to the COMSOL Multiphysics Model

Solution
40 MHz



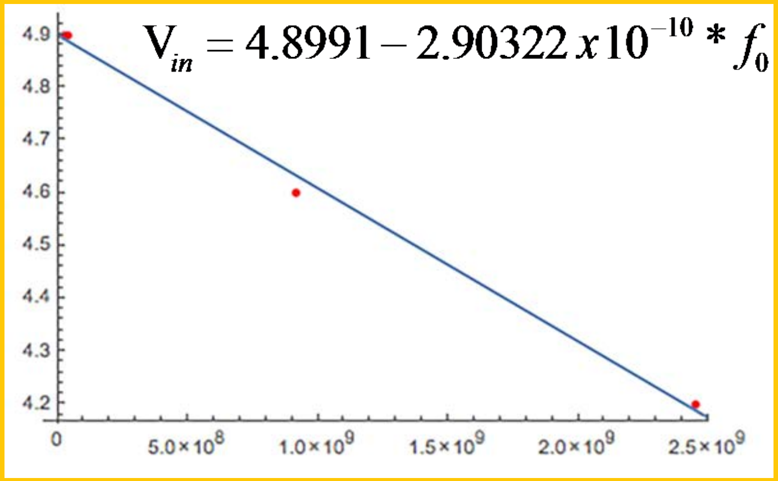
Dielectric Heating: Solutions to the COMSOL Multiphysics Model

Solution
27 MHz



Dielectric Heating: Solutions to the COMSOL Multiphysics Model

Input Voltage



Frequency

Dielectric Heating: Conclusions

The Heating Efficiency Increases
As
The Frequency Increases

Thank You!