

# Temperature Profiles in Ceramic Cylinders Produced by Microwave and Millimeter-wave Heating

A.W. Fliflet, S.H. Gold, and R.W. Bruce<sup>1,2</sup>

Plasma Physics Division

D. Lewis III

Materials Science and Technology Division

Naval Research Laboratory

Washington, DC 20375

arne.fliflet@nrl.navy.mil

<sup>1</sup>RWBruce Associates, <sup>2</sup>Icarus Research, Inc.

**Abstract:** To investigate the internal temperature profiles produced in ceramic workpieces during microwave processing we analyze the heating of ceramic cylinders by a plane-wave RF beam for frequencies in the microwave and millimeter-wave regimes. The analysis includes the temperature dependence of the dielectric properties, an effect that can dramatically alter the microwave coupling during the heating process. To approximate the continuous variation of dielectric properties and temperatures, the cylinder was subdivided into thin tubular regions. The nonlinear heat conduction equation is solved by an iterative process.

**Keywords:** ceramics; millimeter-waves; microwave processing

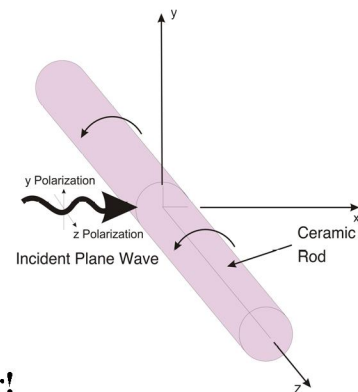
## Introduction

Techniques for processing ceramic materials using microwave or millimeter-wave radiation are being developed as an alternative to the use of conventional furnaces because of several advantages including more rapid processing, improved material properties, and higher overall efficiency. Although microwave processing has been successfully industrialized, there is a need for better modeling of the heating process. The internal temperature profile of the workpiece during processing can greatly impact its quality, but is more difficult to determine in the case of microwave heating than for conventional furnaces. This is because microwave power deposition depends on the workpiece dielectric properties as well as its size and shape. The analysis is further complicated by the temperature dependence of these properties and by the difficulty of solving Maxwell's Equations in all but the simplest cases. In this paper we analyze the heating of ceramic cylinders by a plane-wave RF beam for frequencies in the microwave and millimeter-wave regimes. This configuration has the advantage that the electromagnetic fields are readily obtained even for non-uniform temperature distributions. Although it has been most closely realized in the millimeter-wave regime the results are relevant to microwave cavity furnaces. The results show that the workpiece temperature profile produced by volumetric microwave heating in a cold-walled furnace

varies greatly and depends on the material properties, RF frequency and polarization, and average temperature.

## Model

Consider the steady-state heating of a rotating 2-cm diameter ceramic cylinder by a plane-wave propagating in the x-direction. The cylinder axis is oriented in the z-direction and the electric field is polarized in the z-direction (or y-direction) as shown schematically in Figure 1. The cylinder is assumed to be rotating fast enough ( $\sim 1$  revolution per second) to obtain sufficiently azimuthally uniform heating that only the radial dependence of the dielectric properties and radial heat flow need be included. To approximate the continuous variation of dielectric properties and temperatures, the workpiece is subdivided into 20 thin concentric tubes in which the dielectric and other material properties are held constant. Maxwell's equations are solved by expanding the RF fields in cylindrical waves. Matching the boundary conditions at the tube interfaces leads to a set of equations for the expansion coefficients. The radial heat-conduction equation is nonlinear and is solved numerically by an iterative process. Both transient and steady-state solutions have been investigated. When solving the heat conduction equation, the tube dielectric and thermal parameters and the RF field expansion coefficients are recalculated after each time step or iteration. This leads to a *self-consistent* RF-thermal solution.

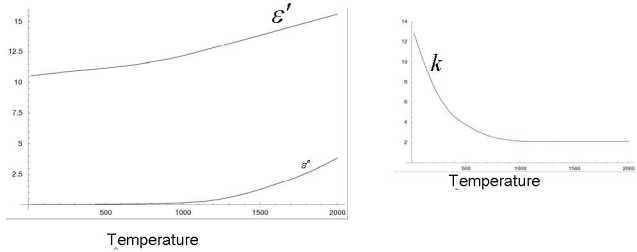


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Figure 1. Rotating ceramic rod heated by a polarized, 83-GHz beam in cold-walled furnace

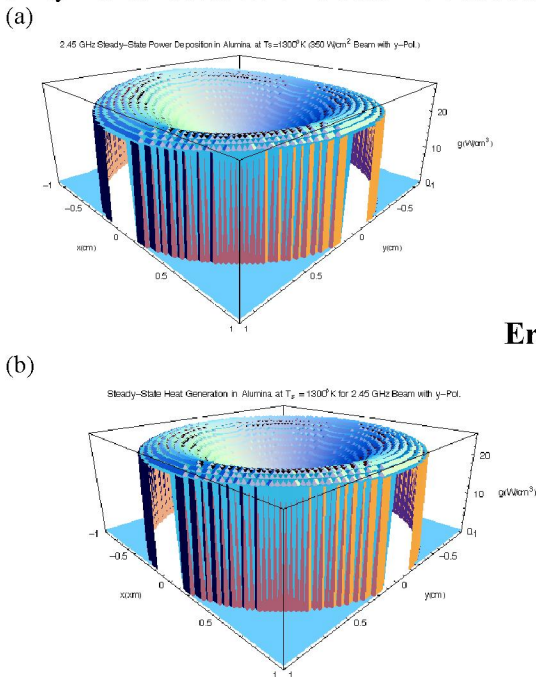
## Results and Discussion

The dielectric constants for sintered high purity alumina are plotted as a function of temperature in Fig. 2, which also shows the temperature dependence of the alumina heat conductivity. The figure shows the imaginary part increasing rapidly with temperature, a characteristic of many oxide ceramics.



**Figure 2.** (a) Temperature dependence of the real and imaginary parts of the dielectric constant of alumina, (b) temperature dependence of alumina heat conductivity.

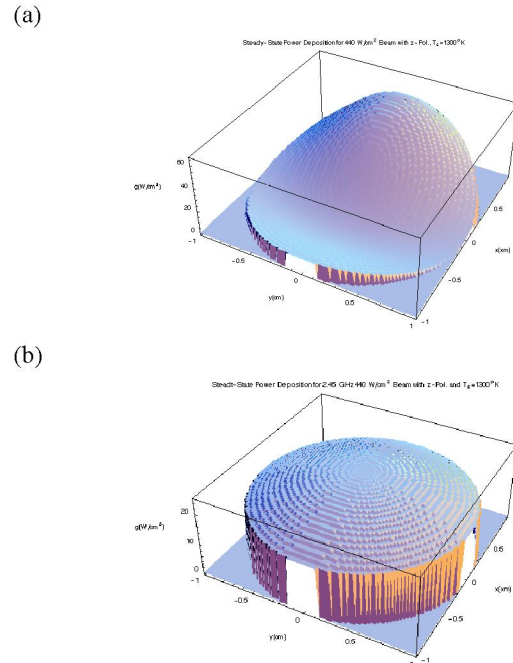
The steady-state microwave power deposition density in the alumina cylinder is shown in Fig. 3(a) for a 2.45 GHz plane wave polarized in the y-direction and incident from the  $-x$  direction. The corresponding azimuthally averaged power deposition is shown in Figure 3(b). The steady-state surface temperature is 1300K. The similarity between the averaged and non-averaged power deposition indicates that the scattering is mainly isotropic although six cylindrical waves were included in the calculation.



**Figure 3.** Power deposition by a 2.45 GHz, y-polarized beam in a rotating alumina cylinder. (a) Instantaneous deposition, (b) averaged deposition.

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Fig. 4 shows the corresponding results for a plane wave polarized in the z-direction. In this case the scattering is not isotropic and the power deposition peaks in the cylinder region opposite to the incident beam. The azimuthal averaging significantly reduces the power density variation for this polarization and the temperature varies from 1300K at the surface to 1400K at the center.



**Figure 4.** Steady-state power deposition for a 2.45 GHz, z-polarized beam in a rotating alumina cylinder. (a) Instantaneous deposition, (b) averaged deposition.

Calculations have also been carried out for an 83 GHz beam (not shown) and show several features believed to be typical for millimeter-wave heating of low-loss oxide ceramics: 1) At low temperatures (up to several hundred °C), where the loss-tangent is low, the cylinder acts like a high-refractive index lens focusing the beam to a region near the center of the cylinder. In addition, the temperature dependence of the permittivity causes resonance effects leading to sudden changes in power deposition. 2) At intermediate temperatures ( $\sim 400 - 1200^\circ\text{C}$ ), the rapid increase in the loss tangent leads to rapid heating with little or no increase in the applied beam power (thermal runaway effect). 3) At high temperatures ( $\sim 1200 - 2000^\circ\text{C}$ ) the loss tangent is so large that the microwaves are absorbed in the outer region of the cylinder.

## Acknowledgment

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