A quasi-analytic model has been developed to examine energy conversion during the microwave sintering of a ceramic that is surrounded by a susceptor. Low-loss ceramics, such as ZrO$_2$, couple poorly with microwave radiation at low temperatures; however, because the dielectric loss usually increases rapidly as temperature increases, coupling improves dramatically at high temperatures. To improve heat transfer at low temperatures, susceptors are used. Three processes of energy flow are considered: microwave absorption due to dielectric losses, blackbody radiation, and heat convection. As expected, the susceptor (SiC) heats rapidly, relative to the ceramic (ZrO$_2$), at low temperatures; however, the ceramic attains higher temperatures after a prolonged period of microwave exposure. Below a critical temperature (800°C), the primary heat-transfer mechanism to the ZrO$_2$ is blackbody radiation from the susceptor. Above this temperature, microwave radiation is the main source that contributes to the temperature increase of the ceramic. The results of the simulation are in reasonable agreement with recent experimental data.

I. Introduction

Ceramic sintering is a fast-growing area of microwave applications. The advantages over conventional heating include rapid heating rates, uniformity, and low power requirements. Zirconia (ZrO$_2$)$^2$ and alumina (Al$_2$O$_3$)$^3$ are low-loss ceramics that couple poorly to microwave radiation at low temperatures. However, because dielectric loss usually increases as temperature increases (by five orders of magnitude in the case of ZrO$_2$ when the temperature increases from 300°C to 1500°C), ceramics can be made absorptive by increasing their temperature. A simple technique to implement such heating is to surround the specimen with a susceptor; silicon carbide (SiC)$^4$ is commonly used for this purpose. Several configurations have been suggested for heating ZrO$_2$ and Al$_2$O$_3$ with a SiC susceptor. Dé et al.$^5$ used a SiC-lined susceptor that surrounded the specimen to sinter Al$_2$O$_3$ compacts. Janney et al.$^6$ suggested an array of SiC rods to sinter ZrO$_2$, and Ramesh et al.$^7$ used a hybrid microwave-heating configuration for ZrO$_2$ and Al$_2$O$_3$ compacts.

In this study, a simple model has been used to investigate energy flow during the sintering of a small ZrO$_2$ sample that was surrounded by a susceptor. Contrary to other models$^8$ where multiple reflections are ignored, these reflections have been considered in the present study because they have an important role, because of (i) spatial discontinuities of the dielectric coefficient in various regions and (ii) rapid variations of the dielectric coefficient, as a function of temperature. Figure 1 shows a schematic illustration of the system. ZrO$_2$ is the ceramic to be sintered and is located in the center of the system; SiC acts as a susceptor, whereas Al$_2$O$_3$ acts as an insulator that confines the heat to the vicinity of the ZrO$_2$. Note that the analysis that follows is suitable for any low-loss ceramic when the dependence of the complex dielectric coefficient on temperature is known. For ZrO$_2$, SiC, and Al$_2$O$_3$, the dependence is shown in Fig. 2; this parametric dependence (ε(7)) tacitly will be assumed to be known, regardless of the physical or chemical mechanism that controls the specific behavior. The temperature dependence of the dielectric coefficient clearly has a major role in the energy-conversion process, either directly or indirectly via reflections. Our goal in this study is to determine the temperature dynamics (spatial and temporal variations) for all regions in space and examine the effect of geometric parameters; all the other variables can be established after the temperature is known.

Microwave radiation is the only source of external power; to evaluate the temperature dynamics, it is averaged over time because any temperature–time variations are much slower than the typical variation of the radiation field. Energy flow between the various regions is assumed to be controlled by two nonlinear processes: blackbody radiation and heat convection. To simulate such a system, a theoretical model has been formulated. Simulations indicate that the energy transfer may be divided into two domains: (i) below a critical temperature $T_c$, the temperature of the ZrO$_2$ and Al$_2$O$_3$ varies slowly, whereas that of the SiC increases rapidly; (ii) at temperatures above $T_c$, the temperature of the ZrO$_2$ steeply increases, overtaking the temperature of the SiC. $T_c$ is defined by the temperature of the ceramic being equal to that of the susceptor and occurs at a time $\tau_c$. For the same time, the Al$_2$O$_3$ insulator shows only a small increase in temperature. The values of $T_c$ and $\tau_c$ are dependent on the volume of the ZrO$_2$ sample and its emissivity (the latter of which is defined as the ratio of the total emissive power of a material to that of a blackbody at the same temperature). This quasi-analytic approach makes it possible to determine the relative influence of the blackbody radiation and