Impact of thermal shielding on heating efficiency of SiC in single mode microwave resonant cavity

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***Abstract*— Microwave heating of a susceptor in the form of SiC disc was simulated in a single mode resonant cavity. The microwave applicator consisted of a waveguide of rectangular cross section WR340 excited by dominant TE10 mode at the industrial frequency 2.45 GHz. Heating efficiency was investigated in two principal configurations represented by 1) an exposed susceptor and 2) a susceptor surrounded with thermal shielding in the form of three coaxial tubes of microwave transparent ceramics. It was found that a relatively high value of the real part of dielectric permittivity of the insulation ceramics leads to a non-negligible modification of the field pattern inside the cavity. This could significantly improve heating efficiency. Consequently, for the design of an efficient microwave applicator, actual sample as well as insulation geometry and dielectric properties should be highly regarded. The analysis has been supported by experiment.**

Keywords*— *microwave heating, single mode resonator, heating efficiency, silicon carbide

I. INTRODUCTION

Microwave energy is used in increasingly more and more areas of technology for its outstanding performance and efficiency [1-5]. With regard to heating applications, it is volumetric, targeted and fast. High temperature microwave applicators, which are employed for instance for ceramics and metal sintering, solid state syntheses or glassmaking, often comprise heat shielding for the sake of efficiency and temperature homogeneity. The heat insulation mostly takes form of assemblies of refractory bricks, wool and other vessels with very low dielectric loss surrounding the sample. Often compounds of Al2O3 and or SiO2 are used as heat insulation materials [1,5]. They fulfill the following conditions with respect to application for microwaves: low thermal conductivity, high melting point, very low loss and chemical durability.

SiC is an extremely common microwave susceptor [1, 3, 5]. It is used in "low" temperature technology in the form of a reaction vessel in organic syntheses. On the other hand, ceramics sintering is an example of its high temperature application.

This study models and analyses behavior and effect of heat insulation during high temperature processing of SiC inside a single mode cavity. In fact, computational treatment of high temperature microwave processing usually puts main focus to the sample while sample support and heat insulation elements are simplified. It is shown that more precise definition of the insulation should provide more realistic results.

II. MICROWAVE APLICATOR

The applicator for microwave heating is in the form of a single mode resonator. The system is fed through the waveguide of rectangular cross section with metallic walls WR340 by dominant TE10 mode at the industrial frequency 2.45 GHz. The resonator sketch is shown in Fig. 1. The waveguide is terminated by a sliding short used to match the structure to get maximum power lost in the heated disc. The applicator consists of a quartz glass tube inserted into a vertical waveguide of circular cross section. The tube separates the sensitive parts of the microwave system from the working volume. The vertical waveguide is at 2.45 GHz under cut-off as the cut-off frequency for its diameter equal to 50 mm is 3.5 GHz assuming waveguide filled by air.

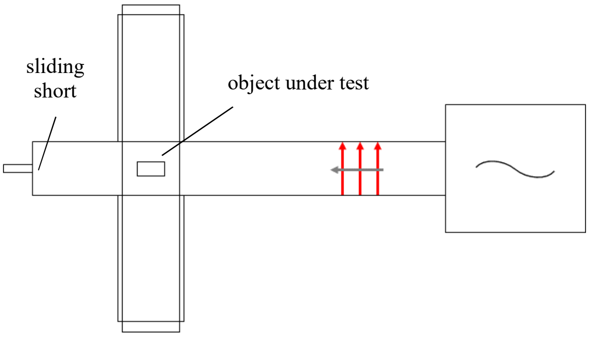

Fig. 1 Sketch of single mode resonator. Details of the sample position are presented in Fig. 2.

Dimensions of the heat insulation were selected such that the entire diameter of the vertical waveguide is utilized. Hence, it was possible to apply three concentric tubes in total making a very potent heat insulation hindering heat loss by radiation and convective transport. In result, the insulation assembly could accommodate a sample with 15 mm diameter.

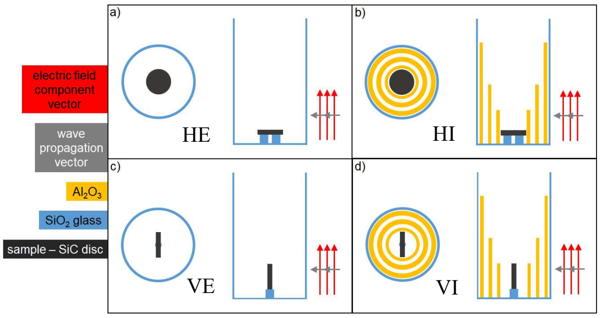

Fig. 2 Scheme of two experimental configurations and two sample orientations in single mode resonator; (a) horizontal placement in exposed configuration, further abbreaviated as HE, (b) horizontal placement with thermal insulation – HI, (c) vertical placement in exposed configuration – VE, (d) vertical placement with thermal

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insulation – VI. Red arrows show the electric field intensity orientation originating from the TE_{10} mode feeding the structure through the waveguide of rectagular cross section. Images lie in x-z plane.

Discs composed of hexagonal SiC are used as samples to be heated. Dielectric properties of SiC were taken from [6]. Real part of relative permittivity is equal to 9.66, loss tangent is equal to 0.1. These values correspond to a lower temperature regime of operation. Temperature dependence is not considered. The SiC disc is inserted into the cavity in two principal positions: horizontal position and vertical position, see Fig. 2.

III. ANALYSIS

Analysis of the single mode resonant cavity shown in Fig. 1 was performed by the Computer Simulation Technology Microwave Studio (CST MwS) [7]. The feeding port is the waveguide port at the waveguide of the rectangular cross section. The ends of the vertical waveguide of circular cross section are in the model again terminated by waveguide ports. The analysis is performed without taking into account accompanied thermal effects. The performed analysis gives as result the value of power lost due to thermal losses in the SiC disc. This power represents only a normalized value corresponding to the normalized amplitude of feeding TE_{10} mode in the waveguide port. The power is calculated as

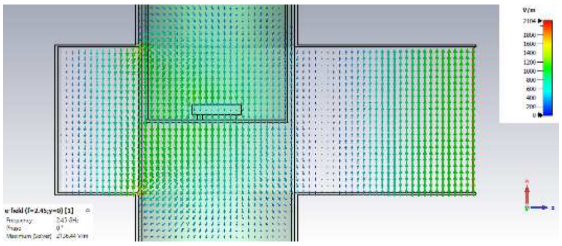
$$P = \frac{1}{2}\iiint \omega\epsilon_r''\epsilon_0|E|^2 dV, \qquad (1)$$

where ω is angular frequency, $\epsilon_r''\epsilon_0$ is product of imaginary part of relative permittivity and permittivity of vacuum, E is electric field intensity, integration is performed over the SiC disc volume. The integral in (1) is calculated by the CST MwS. The imaginary part of relative permittivity is defined by the loss factor tanδ_e or by material conductivity σ

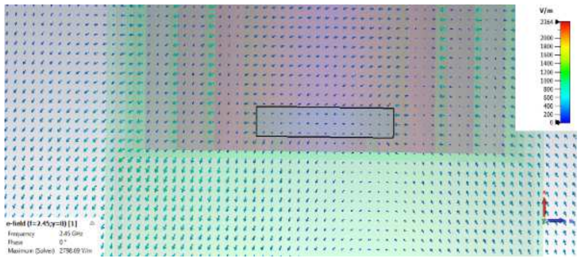
$$\epsilon_r'' = \epsilon_r \tan\delta_e = \frac{\sigma}{\omega\epsilon_0}. \qquad (2)$$

Load matching optimization, in the form of adjusting waveguide length (sliding short) and sample position in the vertical sense, have been performed in several iterations such that maximal losses in the sample have been found.

Fig. 3 shows the calculated distribution of electric field vector across the structure with the horizontal position of SiC disc, see Fig. 2a,b. In HE arrangement, Fig. 3a, the simulation shows that the electric field vector is oriented vertically. Due to boundary condition, the electric field inside the disc is perpendicular to the disc base and is ϵ_r times lower then outside, where ϵ_r is SiC permittivity (9.66). Here, the power loss in the SiC disc is equal to 0.000898 W. However, in HI arrangement, Fig. 3b, it is obvious that the original vertical orientation of the electric field becomes altered. Within the sample and its vicinity, the field becomes oriented horizontally. This leads to a large proportion of the sample surface aligned with the electric field. In this case the boundary condition dictates a high intensity of the field (equal to the field out of disc) and thus high power absorption. The power loss is equal to 0.001660 W.



a) **HE** 0.000898 W

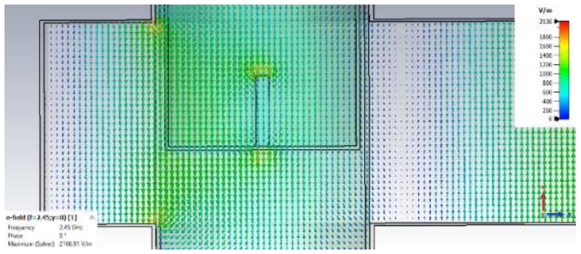


b) **HI** 0.001660 W

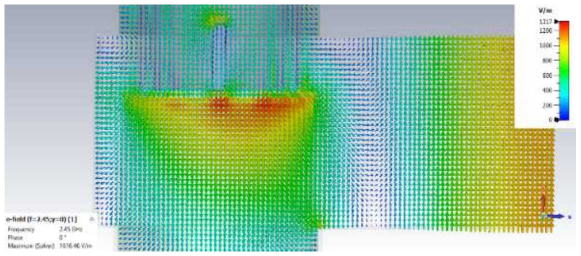
Fig. 3 Distribution of the electric field intensity in the volume of the resonator in the x-z plane; (a) HE, (b) HI.

For the vertical disc position, VE, VI, see Fig. 2c,d, the resulting situation is different, see Fig. 4. In VE arrangement, the electric field vector is parallel to the disc bases, therefore its maximum is inside the SiC material. The power loss for this arrangement is equal to 0.006580 W. In VI arrangement, the field distribution is nearly the same as for the VE arrangement in terms of the field pattern in the sample and the sample vicinity. However, it must be pointed out that load matching and high resonance state in VI arrangement are not achieved until an optimal sample vertical position is found. This particular position is more upwards in comparison with other arrangements. The power loss is equal to 0.002610 W.

There is obvious another effect of the insulation. In the horizontal sample placement (HI), presence of the insulation leads to rotation of the electric field vector in the sample vicinity by ~ 90°. On the other hand, when the sample is oriented vertically (VI), there is no such a rotation.



a) **VE** 0.006580 W



b) **VI** 0.002610 W

Fig. 4 Distribution of the electric field intensity in the volume of the resonator in the x-z plane; (a) VE, (b) VI.

The key cause of the above presented results lies in the relatively high permittivity of Al2O3, $\epsilon_r \sim 10$ [5]. A microwave field passing through a mass of Al2O3 becomes deflected. The heat insulation consists of three layers of Al2O3 vessels separated by air gaps and so the degree of the deflection becomes significant. The reason for this is the behavior of electric field on the surface of a high permittivity dielectric material that to some extent copies the surface of a well conducting material where the electric field vector is perpendicular to this surface.

Comparison of power losses shows that the highest heat generation is realized at the sample vertical exposed arrangement (VE) while the horizontal exposed arrangement (HE) results in roughly 7 times smaller loss. This has been found to be caused by a strong geometrical dependence in the interaction of the sample and the field. Power losses in arrangements comprising heat insulation are roughly in the middle of the above two. The heat insulation improves the heat distribution in the sample and minimizes thermal losses. The influence of the thermal insulation significantly improves the homogeneity of the electric field intensity distribution in the studied structure HI and therefore the homogeneity of the resulting temperature distribution. Fig. 5 presents the field distribution displayed in x-y plane for the case of sample in HI arrangement.

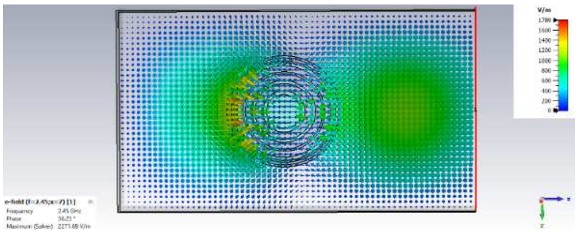


Fig. 5 Distribution of the electric field intensity in the volume of the resonator in the x-y plane; HI arrangement. The plot shows the homogeneous field distribution.

IV. EXPERIMENTAL RESULTS

Experiments were performed with feeding power load up to 800 W. Sample surface temperature was measured with a MICRO-EPSILON ratio pyrometer operating in the temperature range 650°C – 1800°C at the wavelength of 1 µm. Optimal load matching for the lowest reflected power was attained by adjustment of the position of the sliding short, sample vertical position and triple stub tuner connected between the microwave generator and the resonator (not shown in Fig. 1).

Experiments were pursued in the HE and HI arrangements. A sufficient temperature increase of the sample, i.e. over 650°C, being the low temperature limit of the pyrometer, was attained from 200 up to 300 W of feeding power. Actually, below feeding power equal to 200 W, most of the power was reflected from the resonator. Results are summarized as a plot in Fig. 6. Temperatures plotted in Fig. 6 are steady state values that represent maximal values.

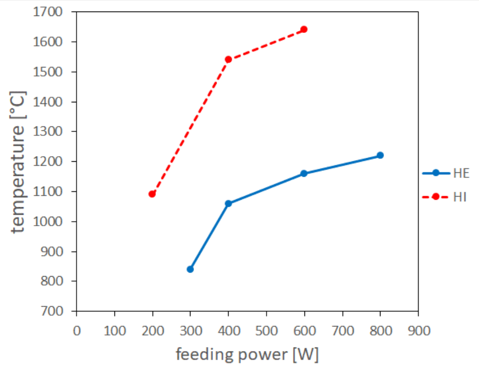


Fig. 6 Plots of temperature – power curves for heating experiments.

Experimental results show that the sample with heat insulation indeed reached significantly higher temperatures in comparison with the exposed sample. This justifies results of performed analysis shown in Fig. 3.

The expression (black body radiation)

$$P = e\sigma_{\mathrm{SB}}A\left(T_{sample}^4 - T_{surroundings}^4\right) \qquad (3)$$

was employed for assessments of heat loss by radiation where P stands for total radiated power, e for sample emissivity taken to be equal to 1, σ_{SB} represents Stefan-Boltzmann constant ($5.670374419 \times 10^{-8}$ Wm^{-2}K^{-4}), A is sample surface (disk of diameter equal to 15 mm, and 1.5 mm in height) and T is temperature in Kelvin [8]. For input power equal to 600 W (3) gives $T_{\mathrm{HE}} = 1160$°C, $T_{\mathrm{HI}} = 1640$°C, and the corresponding radiated powers are $P_{\mathrm{HE}} = 118$ W and $P_{\mathrm{HI}} = 375$ W. These powers represent the thermal radiation from SiC disk, and they should be in the equilibrium state equal to the powers lost in the SiC disk (1). Their ratio is 3.18 that does not correspond to the ratio of the powers calculated by the CST MwS, see Fig. 3. Numerical analysis described in the previous paragraph resulted in powers determined by (1) equal to 0.000898 W for HE, and 0.001660 W for HI. The ratio of these values is 1.85 that is lower than the ratio of powers P_{HE} and P_{HI}. Formula (3) takes into account only radiation of thermal energy, not energy guided, and other effects as the influence of thermal shielding. Therefore, it is not simple to compare values P_{HE} and P_{HI} with the powers calculated in the previous paragraph by (1) where only normalized amplitudes of exciting dominant TE_{10} mode have been used. The dependence if SiC permittivity on temperature is not taken into account.

V. CONCLUSIONS

The paper theoretically investigates behavior of thermal shielding in a single mode resonant cavity for microwave heating experiments. The shielding comprises three coaxial Al_2O_3 tubes representing typical microwave transparent refractory ceramics employed as heat insulation of a SiC sample. Presence of the thermal shielding results in an alteration of the field distribution due to a relatively high value of ϵ_r of Al_2O_3. This has consequences for power losses in the sample. The highest heat generation can be achieved without thermal shielding but sample geometry plays an important role. With the shielding present, heat generation decreases but is still favorable and the effect of sample geometry is less important. However, it is understood that the total heating efficiency is superior with heat insulation as it inherently slows down heat flow out of the sample.

It is evident that a practical realization of an efficient microwave heating system should regard actual sample as well as insulation geometry and dielectric properties.

For better agreement of results, some calibration of the performed experiment and of the numerical analysis must be used. The application of the black body radiation is not straightforward.

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