Computational Characterization of a Millimeter-Wave Heat Exchanger with AlN:Mo Cylindrical Susceptors

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INTRODUCTION

A new type of electromagnetic (EM) heat exchangers (HX) has been recently introduced for ground-to-ground millimeter-wave (MMW) power beaming applications [1]. It comprises an assembly of ceramic elements and a metal baseplate that contains channels with fluid flow. The EM power of the incident wave is dissipated in the ceramic elements and heats the baseplate and the fluid taking the heat away. Computational studies of the MMW HX with a susceptor as a single rectangular block of a ceramic composite (AlN:Mo) [2] have shown elevated energy efficiency and excellent uniformity of the temperature field. However, while these results further stimulated the development of the technology, the cost-effective production of the ceramic parts and practicality of use suggest a physical prototype of the MMW HX to use multiple cylindrical susceptors.

Here we present computational results demonstrating feasibility of the design of the experimental system made of five AlN:Mo cylinders on a square baseplate and compare it with the systems whose layouts are suggested by the highest density packing of equal circles in a square [3]. We show that, in the designs of different geometry, maximum energy efficiency can be achieved using the composites with different concentration of molybdenum, whereas all the considered materials provide excellent uniformity of temperature distribution within the ceramic cylinders.

METHODOLOGY

Computational experiments were conducted following the approach based on the coupled EM-thermal simulation and reported in [2]. The simulation was carried out with the finite-difference time-domain technique implemented in *QuickWave* [4]. The main model reproduces the prospective experimental system which consists of an array of five cylindrical susceptors on a thin metal plate and irradiated by a plane wave (95 GHz), as shown in Figure 1. The layout features an air gap between the points of cylinders' contacts that is required to accommodate thermal expansion of the ceramic material.

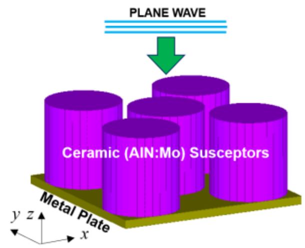
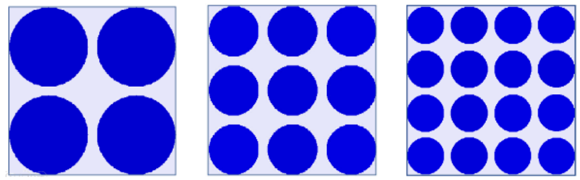
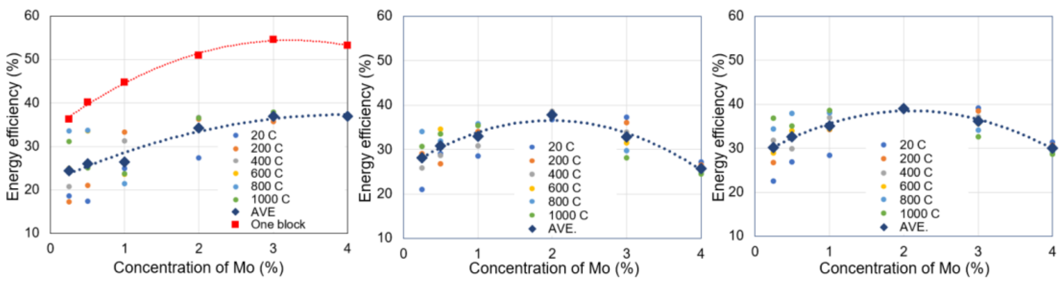


Figure 1. Model of the physical prototype; air gap between the contact points 1 mm.



(a) (b) (c)

Figure 2. Layouts of cylinders in the packings of equal n circles in a square for n = 4 (a), n = 9 (b), and n = 16 (c) with 1 mm gap between the contact points.



(a) (b) (c)

Figure 3. Energy efficiency (at different temperatures of the AlN:Mo composite and average) of the physical prototype (a) and the systems with four (Figure 2(a)) (b) and 9 (Figure 2(b)) (c) cylinders as functions of Mo contents; red points in (a) – the system with one rectangular block.

The susceptor is made of aluminum nitride (AlN) doped with molybdenum (Mo). Data on the materials with six different Mo concentrations from 0.25% to 4.0% (by volume) are detailed in [2] and includes temperature-dependent dielectric constants and the loss factors (at 95 GHz) as well as specific heats and thermal conductivities.

The design in Figure 1 has the ratio of the absorbing area to the area of the square baseplate as d = 0.598. This implies that the layout may cause lower energy efficiency (compared to a single susceptor [1]-[2] with d = 1). The problem on the packing of equal circles in a square [3] provides the highest value of d (0.785) for four, nine, and sixteen cylinders arranged in rows and columns. This suggests the layouts of the cylinders shown in Figure 2 as possible alternative designs. Additional models reproducing these three configurations were developed and employed for the comparative computational analysis.

RESULTS

EM simulation of the 5-cylinder model (radius 4.8 mm, height 10 mm, metal plate 24.4 × 24.4 mm) displays the highest energy efficiency (defined as ratio of the total absorbed power to the power of the incident field) when the cylinders are made of the composite with 3.0-4.0% Mo (Figure 3(a)). This is consistent with the results for the system with a single rectangular block [2], though here the efficiency is notably down. The graphs for both the 4- and 9-cylinder systems (Figure 3 (a), (b)) have maxima of average energy efficiency at about the same level, but for Mo = 2.0%.

Simulation of the temperature field induced in the ceramic composite by the incident MMW field shows that distribution of temperature along the z-axis is highly

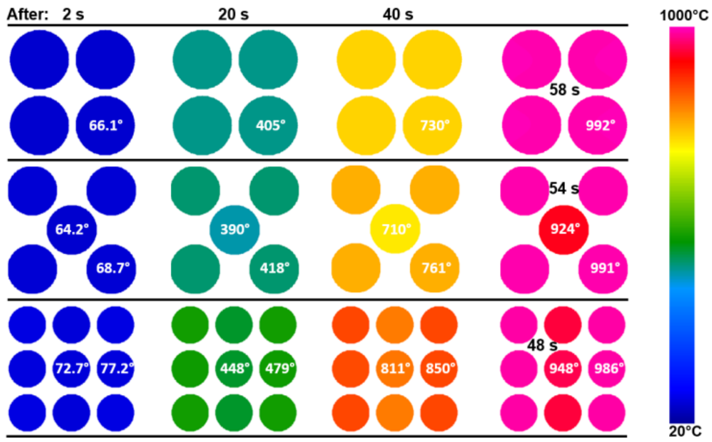


Figure 4. Simulated temperature field in the central cross-sections (the *xy*-plane) of the systems with n = 4, 5, and 9; Mo concentration 3%; incoming power density 357 W/mm^2

uniform in all systems. Typical temperature patterns in the *xy*-plane are shown in Figure 4. In the 4-cylinder model, the temperature distribution is most consistent: all cylinders are heated at about the same rate with very similar patterns. In the systems with higher n, the central cylinder is heated slower and at the final stage its maximum temperature can be lower by 40-60^{o}C. While the 4-cylinder system takes the longest to reach 1,000^{o}C, the delay is only 10 s in comparison with the 9-cylinder system, which is the fastest.

DISCUSSION AND CONCLUSION

As the models with four, nine, and sixteen cylinders were selected due to their high densities in the circles in a square packing problem [3], their densities with the 1 mm gap turned out to be 0.722, 0.662, and 0.605, respectively. Despite these higher densities, the energy efficiency of the tested models is about the same as the 5-cylinder model (0.598). The energy efficiency of all considered scenarios drops significantly when compared to the single rectangular model (54 to 37%). For the 5-cylinder system, energy efficiency is at its maximum when the material has 3.0-4.0% Mo, while the 4 and 9 cylinders displayed their maxima at 2.0%. Satisfactory uniformity of temperature distribution in the cross-sectional plane is seen in all the layouts and all the materials.

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