Modeling of Hybrid Heating of Limestone by Microwaves and Thermal Radiation

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Practically valuable scenarios of hybrid (heat radiation and microwave) thermal processing of materials are consdered from a modeling prospective. The algorithm of multiphysics (electromagnetic and thermal) simulation is implemented by coupling the model of radiation in ANSYS Fluent with the electromagnetic models in QuickWave-3D. For hybrid heating of cylindrical samples of limestone in Ceralink's MAT^{TM} kiln, time-temperature history of the heating process is simulated along with patterns of the temperature field. Hybrid heating is shown to be more efficient in terms of heating rate and temperature uniformity.

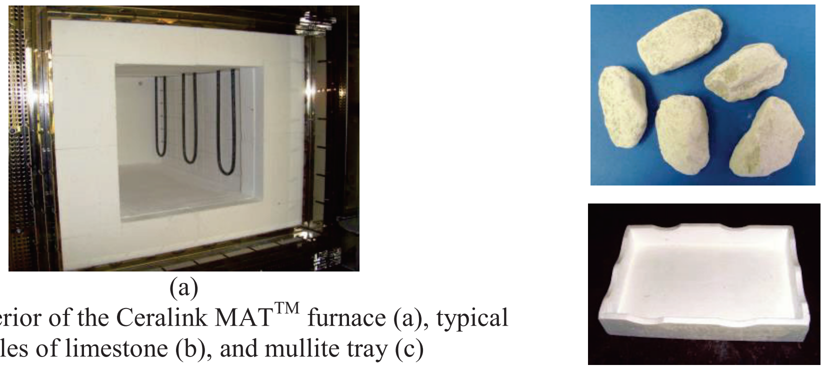
Keywords: Ceramics, microwave heating, multiphysics modeling, thermal analysis

INTRDOCTION

The imperative need for alternative sources of energy and efficient energy use has recently initiated an array of insightful studies in microwave (MW) power engineering. MW heating is known for its ability to improve the efficiency and quality of applied thermal processes, but the intrinsic non-uniformity of MW-induced temperature fields remains a factor limiting the range and productivity of the related industrial technologies.

Among different approaches addressing this issue, there is a hybrid technique combining MW heating with conventional thermal processing when latter and former are responsible for treatment of the exterior and interior of the product, respectively (e.g., [1], [2]). While this technique has demonstrated a strong potential for certain industrial applications, corresponding applicators have always been developed on the basis of expensive and inefficient cut-and-try experimentation. Indeed, the known attempts to model heating by MW and thermal radiation [3]-[5] have had quite limited capabilities in terms of both electromagnetic (EM) and computational fluid dynamics (CFD) analyses.

In this paper, we present new modeling results produced from our original technique capable of more adequately simulating processes in specialized hybrid systems. The technique is based on radiative boundary conditions incorporated into multiphysics (EM and thermal (T)) modeling. The algorithm is implemented by making the models of



(a) (b) (c)

Figure 1. Interior of the Ceralink MAT^{TM} furnace (a), typical samples of limestone (b), and mullite tray (c)

radiation in *ANSYS Fluent* available for the EM models in *QuickWave-3D*. The technique was originally reported in [6] as a part of the development of the hybrid technology for high temperature processing of limestone. Here we report new results in modeling of the process of hybrid heating of limestone samples in Ceralink's MAT^{TM} kiln. Two examples of simulated temperature fields are presented; hybrid heating is seen to be more efficient in terms of temperature uniformity.

MODELING TECHNIQUE

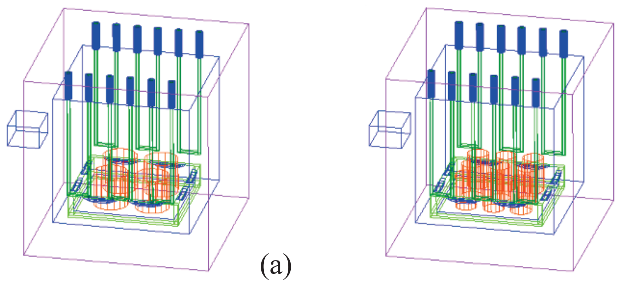
The modeling algorithm applicable to problems involving high temperature processing by both microwaves and heat radiation is based on an advanced EM solver with a full-fledged CFD package offering a variety of models of radiation. A computational tool introduced in [6] uses the 3D conformal FDTD simulator *QuickWave-3D* (*QW-3D*) [7] and the finite element *ANSYS Fluent* [8] solver. The resulting coupled simulation accounts for the radiant boundary conditions (BC) and is applied to hybrid radiative-microwave heating. The model handles not only the heat flow within the sample, but also the radiative heat exchange between the heaters and the material sample.

MICROWAVE SYSTEM AND ITS MODEL

The hybrid MW furnace in this study is Ceralink's MAT^{TM} kiln (Figure 1(a)). It has a cubic metal cavity, and the cavity walls are lined with a thick layer of ceramic insulation with 80 wt% alumina. Raw unprocessed pieces of limestone (Figure 1 (b)) are to be placed on a mullite tray (Figure 1(c)) in the cavity. To speed up the calcination process, six U-shaped heating elements made of molybdenum disilicide ($MoSi_2$) are installed in the cavity near the side walls. The microwaves are delivered into the furnace through a rectangular waveguide connected to the wall opposite to the kiln's door.

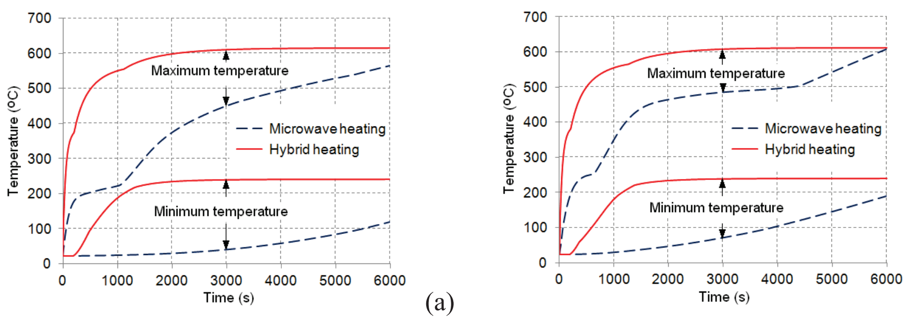
This kiln was represented in a model developed for *QW-3D*. All geometrical features of the furnace were reproduced as they are, except the cylindrical U-shaped heater's tubes which were approximated by three straight segments of square tubing. Limestone pieces, normally of irregular shapes, were represented here in two different modeling scenarios by, respectively, four and nine vertical cylinders symmetrically located in the tray; both scenarios are visualized in Figure 2.

Temperature-dependent EM and T material parameters of all materials in the kiln (i.e., limestone, alumina, and mullite) were experimentally determined in the interval 20-



(a) (b)

Figure 2. 3D view of Ceralink's MAT kiln in *QW-3D*: 4 (a) and 9 (b) limestone cylinders.



(a) (b)

Figure 3. Time-temperature histories of the max and min temperatures in the kiln for MW and hybrid heating: 4 (a) and 9 (b) limestone cylinders.

1,000^{o}C prior to modeling [6]. Because of the high electric conductivity σ of $MoSi_2$, the heaters were assumed to be metallic with finite σ on the surface. Accounting for the magnetron's pulling effect, operating frequency of the system was determined to be 2.431 GHz; the reflection coefficient turned out to be lowest at this frequency for all temperatures of the sample and the insulation. To ensure high accuracy of the solution, the FDTD mesh (nearly 800,000 cells) was optimized and made non-uniform through the model.

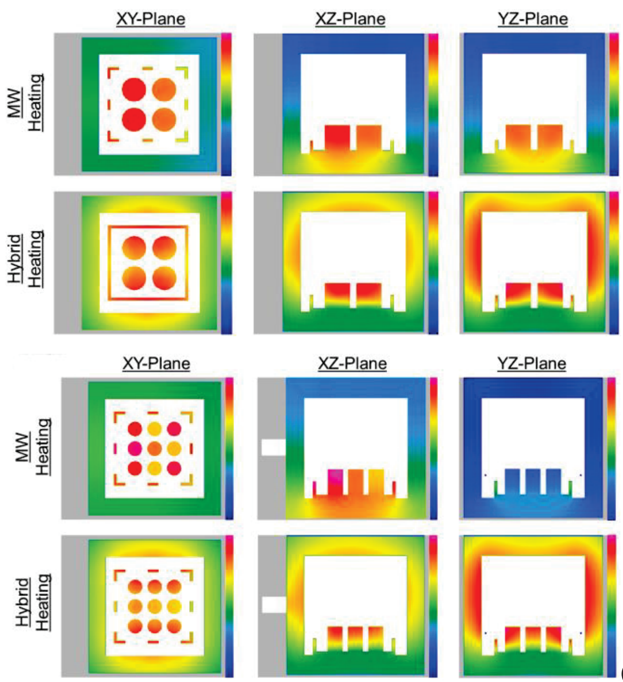
RESULTS

The results of temperature simulations performed for pure microwave and hybrid heating are presented in Figure 4 for 2 kW microwave power and constant (1,000^{o}C) temperature of the heaters. As expected, the hybrid heating greatly contributes to faster growth of the temperature and reduces the differences between the min and max temperatures.

The temperature distributions in the cavity cross-sections (Fig. 4) suggest that with pure microwave heating, the mullite tray absorbs most of the energy whereas the limestone samples remain relatively cool. In the case of hybrid heating, the heat exchange between the heating elements and the cavity mostly affects the temperature of the sample.

CONCLUSION

In this paper, a new computational tool designed for modeling of hybrid (heat radiation and MW) heating in specialized applied systems has been used to model the high-temperature processing of limestone in Ceralink's MAT™ hybrid furnace. The resulting tool allows simulation of temperature distributions generated by hybrid and by purely



(a)

(b)

Figure 4. Temperature patterns in the central coordinate planes after 100 min of MW and hybrid heating: 4 (diameter 74 mm) (a) and 9 (diameter 46 mm) (b) symmetrically placed limestone cylinders of height 74 mm on a mullite tray; microwave power 2 kW. Max temperatures 614 (a) and 618^{o}C (b), min temperature 23^{o}C (a, b).

microwave heating. Comparison of the heating regimes gives us an insight into the operation of the hybrid system and thus should be beneficial in the computational analysis and computer-aided design of such systems.

ACKNOWLEDGMENT

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