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Numerical Simulation of the Production of Ceramic Pigments Using Microwave Radiation: An Energy Efficiency Study Towards the Decarbonization of the Pigment Sector

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Abstract : Global warming mitigation is one of the main challenges of this century, having the net balance of greenhouse gas (GHG) emissions to be null or negative in 2050. Industry electrification is one of the main paths to achieving carbon neutrality within the goals of the Paris Agreement. Microwave heating is becoming a popular industrial heating mechanism due to the absence of direct GHG emissions, but also the rapid, volumetric, and efficient heating. In the present study, a mathematical model is used to simulate the production using microwave heating of two ceramic pigments, at high temperatures (above 1200 Celsius degrees). The two pigments studied were the yellow (Pr, Zr)SiO_2 and the brown (Ti, Sb, Cr)O_2. The chemical conversion of reactants into products was included in the model by using the kinetic triplet obtained with the model-fitting method and experimental data present in the Literature. The coupling between the electromagnetic, thermal, and chemical interfaces was also included. The simulations were computed in COMSOL Multiphysics. The geometry includes a moving plunger to allow for the cavity impedance matching and thus maximize the electromagnetic efficiency. To accomplish this goal, a MATLAB controller was developed to automatically search the position of the moving plunger that guarantees the maximum efficiency. The power is automatically and permanently adjusted during the transient simulation to impose stationary regime and total conversion, the two requisites of every converged solution. Both 2D and 3D geometries were used and a parametric study regarding the axial bed velocity and the heat transfer coefficient at the boundaries was performed. Moreover, a Verification and Validation study was carried out by comparing the conversion profiles obtained numerically with the experimental data available in the Literature; the numerical uncertainty was also estimated to attest to the result's reliability. The results show that the model-fitting method employed in this work is a suitable tool to predict the chemical conversion of reactants into the pigment, showing excellent agreement between the numerical results and the experimental data. Moreover, it was demonstrated that higher velocities lead to higher thermal efficiencies and thus lower energy consumption during the process. This work concludes that the electromagnetic heating of materials having high loss tangent and low thermal conductivity, like ceramic materials, maybe a challenge due to the presence of hot spots, which may jeopardize the product quality or even the experimental apparatus. The MATLAB controller increased the electromagnetic efficiency by 25% and global efficiency of 54% was obtained for the titanate brown pigment. This work shows that electromagnetic heating will be a key technology in the decarbonization of the ceramic sector as reductions up to 98% in the specific GHG emissions were obtained when compared to the conventional process. Furthermore, numerical simulations appear as a suitable technique to be used in the design and optimization of microwave applicators, showing high agreement with experimental data.

Keywords : automatic impedance matching, ceramic pigments, efficiency maximization, high-temperature microwave heating, input power control, numerical simulation
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