Modeling and Energy Analysis of Limestone Decomposition with Microwave Heating

Authors : Sofia N. Gonçalves, Duarte M. S. Albuquerque, José C. F. Pereira

Abstract : The energy transition is spurred by structural changes in energy demand, supply, and prices. Microwave technology was first proposed as a faster alternative for cooking food. It was found that food heated instantly when interacting with high-frequency electromagnetic waves. The dielectric properties account for a material's ability to absorb electromagnetic energy and dissipate this energy in the form of heat. Many energy-intense industries could benefit from electromagnetic heating since many of the raw materials are dielectric at high temperatures. Limestone sedimentary rock is a dielectric material intensively used in the cement industry to produce unslaked lime. A numerical 3D model was implemented in COMSOL Multiphysics to study the limestone continuous processing under microwave heating. The model solves the two-way coupling between the Energy equation and Maxwell's equations as well as the coupling between heat transfer and chemical interfaces. Complementary, a controller was implemented to optimize the overall heating efficiency and control the numerical model stability. This was done by continuously matching the cavity impedance and predicting the required energy for the system, avoiding energy inefficiencies. This controller was developed in MATLAB and successfully fulfilled all these goals. The limestone load influence on thermal decomposition and overall process efficiency was the main object of this study. The procedure considered the Verification and Validation of the chemical kinetics model separately from the coupled model. The chemical model was found to correctly describe the chosen kinetic equation, and the coupled model successfully solved the equations describing the numerical model. The interaction between flow of material and electric field Poynting vector revealed to influence limestone decomposition, as a result from the low dielectric properties of limestone. The numerical model considered this effect and took advantage from this interaction. The model was demonstrated to be highly unstable when solving non-linear temperature distributions. Limestone has a dielectric loss response that increases with temperature and has low thermal conductivity. For this reason, limestone is prone to produce thermal runaway under electromagnetic heating, as well as numerical model instabilities. Five different scenarios were tested by considering a material fill ratio of 30%, 50%, 65%, 80%, and 100%. Simulating the tube rotation for mixing enhancement was proven to be beneficial and crucial for all loads considered. When uniform temperature distribution is accomplished, the electromagnetic field and material interaction is facilitated. The results pointed out the inefficient development of the electric field within the bed for 30% fill ratio. The thermal efficiency showed the propensity to stabilize around 90%for loads higher than 50%. The process accomplished a maximum microwave efficiency of 75% for the 80% fill ratio, sustaining that the tube has an optimal fill of material. Electric field peak detachment was observed for the case with 100% fill ratio, justifying the lower efficiencies compared to 80%. Microwave technology has been demonstrated to be an important ally for the decarbonization of the cement industry.

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