Modeling of Limestone Calcination Using Joule Heating

Ravichand Kancharla*, Ramakrishna Machiraju
Department of Chemical Engineering, Padmasri Dr. B.V.Raju Institute of Technology, Narsapur, Medak Dist – 522301
*Corresponding Author e-mail: ravichand.kancharla@bvrit.ac.in

Abstract—The limestone calcination reaction is endothermic (CaCO$_3$ $\Rightarrow$ CaO + CO$_2$, $\Delta H = 1660$ kJ /kg) which means that higher temperatures favor the forward reaction. The reaction will proceed only if the partial pressure of CO$_2$ in the gas above the solid surface is less than the decomposition pressure of the CaCO$_3$. All researchers found that the presence of CO$_2$ inhibited the calcination reaction, but the form of dependence is uncertain. As the reaction is endothermic, the conventional process for calcinations uses coal firing in rotary kiln with limestone feed to get the desired temperatures. This generates CO$_2$ in the process leading to inhibition of calcination reaction.

Microwave heating of limestone is proposed to increase the temperature of the limestone to the desired levels. Microwave heating is an emerging but underutilized phenomenon in modern industrial applications having the advantages such as: time and energy saving, very rapid heating rates, improved mechanical properties, considerably reduced processing time etc. In the current work, 3D model was created with joule heating (to mimic microwave heating) of 15*15*1 mm limestone block due to lack of RF module at author. Temperature and CO$_2$ concentration profiles were obtained from COMSOL model & were studied with respect to the time. Results from the theoretical model were analyzed and compared with the published data on calcination temperatures and CO$_2$ dependency.

Keywords—Calcination, rapid heating, CO$_2$ concentration.

I. INTRODUCTION

Rapid heating of limestone is one of the recent research interest evaluated by Fall recently [1]. Similar study was performed for Alumina heating by Suryanarayana Murthy et al. [2] using the COMSOL software. This will enable to reduce CO$_2$ concentrations and hence the calcination temperatures in cement production. COMSOL capabilities were demonstrated to model this problem.

II. MODEL & GOVERNING EQUATIONS

A. Joule Heating

15*15*1 mm limestone block was subjected to joule heating (to mimic the microwave heating) for 0-20 minute duration with the governing equation:

$$\rho C_p \frac{dT}{dt} + \rho C_p u_{trans} \nabla T = \nabla \cdot (k \nabla T) + Q + W_p$$

$$\nabla \cdot J = Q_i$$

$$J = \sigma E + \frac{\partial D}{\partial t} + J_e$$

$$E = -\nabla V$$

All surfaces are assumed to be available for heating with the consideration that it is free falling particle. Initial condition was $T=303.15K$ and $V=220$ Volts. Relative permittivity was taken as 7.2 and electrical conductivity was taken as 0.02 S/m for limestone [3].

B. Transport of diluted species

Calcination reaction of limestone with following reaction was considered:

$$CaCO_3 \Rightarrow CaO + CO_2, \Delta H = 1660 \text{ kJ /kg}$$

Parameters for Reaction Rate Constant was taken from Boateng [4], $k= A \exp(-E/RT)$

Where Frequency factor, $A=9.67 \times 10^{24} \text{ hr}^{-1}$

Activation Energy, $E= 1092.947 \text{ KJ/mol}$

Rate expression: $R_j = k \cdot c_j$

Diffusion of CO$_2$ was considered from within the block to the surface with $D_{CO_2} = 1.39e-8 \text{ m}^2/\text{s}$.

Governing equation:

$$\frac{\partial c_i}{\partial t} + \nabla \cdot (-D_i \nabla c_i) = R_i$$

$$N_i = -D_i \nabla c_i$$

Convective flux was considered with the following specification:

Inward flux = 0.1 mol/m$^2$.s

Mass transfer coefficient = 0.0833 m/s

CO$_2$ concentration in bulk phase = 0.002 mol/m$^3$

Some of the conditions / properties are assumed due to lack of data & this model should be used for demonstration purpose only.

Physics controlled mesh with fine element size was used for simulation.

III. RESULTS & DISCUSSION

Heating time required for calcinations was studied for various Inflow heat flux values ranging from 500000 (rapid heating) - 500 W/m$^2$ (slow heating) and the results were shown in Figure 1.
Duration was found to be in the range of 1s to 1200s. In case of slow heating the temperature was uniform throughout the slab. It was also observed that the temperature profile was changing very rapidly at higher flux values & hence an inflow heat flux in the range of 500-5000 W/m² was suggested for actual experiments. Concentration profiles were also captured for the above case study (Figure 2) and found that the CO₂ concentration is leading to uniform value equal to 0.014 mol/m³.

Figure 2. Concentration profile with Heat influx variation.

It was found that the temperature calculations are not very sensitive to step size and the model was converging with a step size of 0.1°C also with an accurate solution. However, Concentration calculation found to be sensitive and even the computation time was considerable.

IV. CONCLUSION

COMSOL capabilities to model limestone calcinations was demonstrated using two physics namely Joule heating and Transport of diluted species. Experimental investigations should be carried out based on the inputs from the COMSOL model. Joule heating is showing a temperature profile across
the slab & hence the study of microwave heating suggested.

V. REFERENCES


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