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Computational fluid dynamics analysis of sponge iron rotary kiln

Gajendra Kumar Gaurav*, Shabina Khanam

Department of Chemical Engineering, Indian Institute of Technology Roorkee, Roorkee 247 667, India

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ABSTRACT

2D CFD model of rotary kiln of sponge iron process is developed to study the effects of angle of inclination, number of rotation and mass flow rate of iron ore on output parameters. Based on grid independent test for temperature profile optimum mesh size is selected. The result shows that optimum angle of inclination, number of rotation and flow rate of iron ore are found as 2.7 degree, 4.8 rpm and 10 kg/s, respectively. At these optimum conditions the % metallization is predicted as 89.5%, which is 3.24% less in comparison to the existing system. The temperature profiles of gas and bed are also found within acceptable temperature limits. The results are compared well with the published work as well as industrial data.

1. Introduction

Rotary kiln is the primary equipment in sponge iron industry, which is used to reduce iron ore to metallic iron i.e. Fe. It is called sponge iron. Rotary kiln is widely used in cement and steel industries. The production capacities of these industries depend significantly on the performance of rotary kiln. The parameters, which affect the performance of rotary kiln, are temperature profile inside the kiln, particle size of raw material, ratio of air to coal, combustion of coal, heat transfer characteristics inside the kiln, etc. It is difficult to understand all these parameters individually due to complex nature of heat transfer along with chemical reactions, which take place inside the kiln. Moreover, it is very much complicated to measure the physical parameters, which influence the performance of the process. These parameters are kiln inclination and rotation, raw material characteristics, etc.

A few researchers focused on sponge iron process and suggested mathematical expressions to model the temperature profile, heat transfer, fuel combustion, reduction chemistry, etc., inside the rotary kiln. They used partial differential equations for solving the energy equation, radiative model equation, viscous model equation etc. of the process [1]. Sass [1] developed a simplified model for heat transfer inside the kiln, which consisted of differential equations. The model did not include simultaneous chemical reactions. The author also developed the correlation for prediction of kiln length. The model was solved through Runge–Kutta method. It was verified with data collected from cement kiln and ore heating kiln for U.S. steel. The author found that the predicted kiln length through simulation was close to the actual length of the kiln. Ghoshdastidar et al. [2] developed a heat transfer steady-state model for non-reacting zone of the rotary kiln, which was used for drying and preheating of wet solids. They used this model to simulate the rotary kiln of cement industry. The developed model was simulated using finite difference technique. They carried out a parametric study related to better design of rotary kiln, which required smaller inclination angle, medium gas flow rate and low rotational speed in the range of 3–5 °, 3–7 kg/s and 1–10 rpm, respectively. Further, they predicted the length of kiln with reasonable accuracy. As focus of the present work is to analyze performance of rotary kiln through CFD a few studies related to it are discussed hereunder:

Mujumdar et al. [3] discussed that rotary kilns are complex systems as these involve the existence of several processes such as reduction and coal combustion, which occur simultaneously in bed as well as freeboard regions. They identified various key issues

* Corresponding author.
E-mail addresses: gajendragaurav@gmail.com (G.K. Gaurav), shabifch@iitr.ac.in (S. Khanam).

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Nomenclature

m_c	mass of char (kg)
k_1	rate of external diffusion in Gibb model (s^{-1})
k_2	rate of surface reaction rate in Gibb model (s^{-1})w
k_3	rate of internal diffusion and surface reaction in Gibb model (s^{-1})
k_c	carbon oxidation rate in Gibb model (m s^{-1})
k_v	char formation rate constant (m s^{-1})
A_v	pre-exponential factor of devolatilization reactions (s^{-1})
A_c	pre-exponential factor of devolatilization reactions (s^{-1})
A_s	constant in Gibbs model
m	mass (kg)
D	External diffusion coefficient of oxygen in Gibb model (m^2 s^{-1})
r_p	particle radius (m)
D_{ref}	reference dynamic diffusivity in Gibb model (kg m^{-1} s^{-1})
T	particle temperature (K)
T_g	Far field gas temp. (K)
R	Reynolds number

related to performance of the rotary kilns of cement industry. These issues were simulated based on CFD models. The authors suggested that whenever a comprehensive model is developed for rotary kilns in cement industry these key issues are required to be examined. Further, Mujumdar and Ranade [4] considered bed as well as freeboard regions as separate sections for simulating these regions at similar time scales. The developed CFD models were coupled through common interface by mass and heat transfer. This approach discussed the burner design along with flame characteristics to improve the kiln performance. They considered that combustion of coal carried out in upper zone (freeboard region) of the kiln and clinkerization reactions occurred in the bed of the kiln. They observed that 1D coupling required less computational time as compared to 2D coupling without affecting the accuracy of predicted results. Further, Mastorakos et al. [5] accounted heat transfer, clinker reactions and flame modeling inside the rotary kiln through CFD. They treated bed and freeboard models as separate domains and coupled them explicitly. They assumed axis-symmetric geometry of kiln and coating formation throughout the length of the kiln. Wang et al. [6] observed heat flux for understanding combustion behavior and thermal effect of clinker formation based on chemical and physical analyses of the process. In terms of CFD code, they obtained gas temperature, velocity and its components in rotary kiln of cement industry. Kolyfetis and Markatos [7] developed a CFD model for coal combustion with heat transfer in the freeboard region. However, they did not consider clinker reactions as well as coating inside the kiln. Karki et al. [8] developed a CFD based 3D model for simulation of combustion and heat transfer simultaneously in the kiln. They used an effective thermal conductivity for defining degree of mixing in the bed region, which helped in visualizing the process effectively. The results predicted by authors provided only the qualitative information of the process.

The CFD studies discussed above are mainly carried out for rotary kiln of cement industry. However, very little work is available related to CFD analysis of rotary kiln of sponge iron process such as: Prasad and Ray [9] developed 2D model to simulate flow pattern of air in rotary kiln of a typical 100 tpd sponge iron plant. They considered different positions of air pipe such as 50 mm, 100 mm, 150 mm and 320 mm above the axis for identifying optimum location. It disturbed the reducing atmosphere in the solid bed region strongly and obtained a well metalized product. The authors found that the optimum location of air pipe was at 320 mm above the axis. Majhi [10] proposed 3D model of the kiln of a typical sponge iron plant having capacity of 500 tpd and simulated through ANSYS 13. He found that granules exposed to freeboard region participated in reduction reaction directly. Gaurav and Khanam [11] developed a CFD model, which was used to discuss the pattern of temperature profiles of the bed and gas zones along the length of the kiln as well as Fe content. Further, Gaurav and Khanam [12] developed a 2D CFD model where variation of % metallization and temperature profile with input parameters were discussed. The results were closely matched with the published

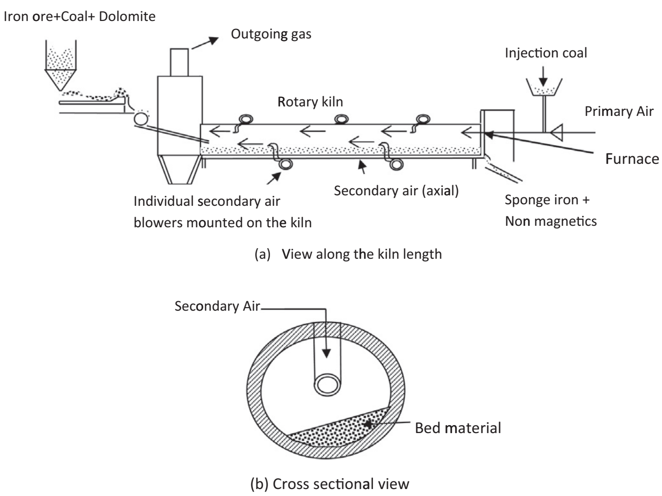

Fig. 1. **(a)** Front view of the rotary kiln **(b)** Cross sectional view of the rotary kiln.