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Research paper

Numerical study of volatiles production, fluid flow and heat transfer in coke ovens

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HIGHLIGHTS

- A mathematical model is developed to describe flow-pyrolysis-thermo behaviors in the coking chamber of coke ovens.
- The simulated coal/coke bed temperatures agree with the experimental data.
- The evolutions of volatile product, bed temperature, gas temperature and flow path are obtained.

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ABSTRACT

A two dimensional transient model of coal carbonization was developed to simulate the coking process including heat transfer and fluid flow in the coking chamber. The multiple independent parallel reaction model was applied to predict the volatiles production. The convective heat transfer between the coal/coke bed and the volatiles was taken into account in the model. The simulated bed temperatures agree with the experimental data. The evolutions of bed temperature, gas temperature, and gas component and flow path were further illustrated. For a typical 6-m-height coke oven, the average temperature in roof space over coal load keeps rising till 14 h; and then shows a slight increase at around 1150 K until the end of the coking process, when the central temperature of the coal/coke bed reaches 1273 K at about 18.1 h. Most gases move from the central plane of coking chamber in the early stage, while they move from the wall side in the later stage with the displacement of the plastic layer. This work is expected to provide useful information for optimizing the operations and design of coke ovens.

1. Introduction

Metallurgical coke is used in iron and steel industry processes (primarily in blast furnaces) to reduce iron ore to iron. Over 90 percent of the total coke production is dedicated to blast furnace operations. Coke is the most important raw material fed into the blast furnace in terms of its effect on blast furnace operation and hot metal quality. The coke-making industry has seen substantial technological development over the past two decades. Several new technologies such as Jumbo coking reactor [1], SCOPE21 [2] (Super coke oven for productivity and environment enhancement toward the 21st century), Non-Recovery ovens [3] have been developed as alternative methods of producing coke.

Although alternative technologies have made some success stories, it is certain that the highly developed conventional regenerative coke oven will continue in the foreseeable future essentially because of its large productivity and the present existence of a large number of ovens. The latest regenerative coke ovens (by-product coke oven batteries) with raw gas recovery have reached dimensions of more than 8 m in height and 90 m^3 in useful oven volume [4].

Conventional regenerative coke making is in a coke oven battery where each coking chamber is sandwiched between heating wall. The coking coal is carbonized under a non-oxidizing atmosphere at a temperature around 1223 K–1323 K up to a certain degree of

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devolatilization to produce metallurgical coke of desired mechanical and thermo-chemical properties. During the coking process, the volatile matter evolved is collected and refined into by-product chemicals [5].

The gas flow and heat transfer of the coking process in the coke oven is difficult to understand because of its complexity. Operations and improvements of the coke oven are mainly based on experience, without corresponding theoretical guidance. To date, few modeling studies of the flow and heat transfer of the coking process were conducted. Merrick [6–10] proposed a series of mathematical (chemistry and kinetics, heat transfer, fluid mechanics) models on the coking process, and gave a preliminary understanding of the process. In Merrick' model, the flow of coke oven gas (COG) was replaced by the steam flowing through the porous media to predict the first stage of the gas flow in the coking chamber. This work is the first published attempt for developing a theoretical model to determine the gas flow distribution in a coke oven and was seen as an initial exploratory work. Guo and Tang [11,12] established a model of the coking process, derived from Merrick' study. The model was solved using the PHOENICS software with a special emphasis on desulfurization. Simulated coking time and the mass fractions of volatile matter deviated some from the reality, probably because Guo and Tang neglected the heat transfer effect caused by the release of volatile matter and overestimated the initial temperature of coal. Z. Buliński, Ł. Słupik, A.J. Nowak et al. [13–15] developed a validated coupled CFD model of a coke oven battery and analyzed the thermal processes within coke oven charge.

Coal pyrolysis is the first step in almost all the processes of coal conversion. Coal pyrolysis model has been widely investigated, a number of kinetic models have been developed for the devolatilization of various coals. Howard [16], Solomon and Hamblen [17] give excellent reviews of these works. Models that are relatively simple includes the single kinetic rate model [18], the two competing rates model [19] and multistep method [20]. With the further understanding of coal molecular structure, network pyrolysis models on coal rapid pyrolysis have been reported, such as FG-DVC(Functional Group-Depolymerization, Vaporization, Cross-Linking) model [21], CPD (Chemical Percolation model for Devolatilization) model [22], Flash Chain (distributed-energy chain) model [23], etc. These network pyrolysis models are applicable over a wide range of coal types for coal rapid pyrolysis, but they are extremely complex and difficult to use for coking process which is a slow devolatilization process.

Up to now, a limited number of studies address the flow and heat transfer in the coking chamber of regenerative coke oven using numerical simulation method. In this work, a two dimensional mathematical model is developed to investigate the temperature profile, the evolution of the volatiles and the flow in detail in the coking chamber. The model takes into account the convective heat transfer between the coal/coke bed and the produced gas, also the heat of reaction. The multiple independent parallel reaction (MIPR) model is applied in the model to forecast the volatile evolution. The emphases of present work are heat transfer, fluid flow and evolution of COG component involved in the coking process. This work would not only be helpful for a better understanding on the coking process, but also help facilitate the optimization of coke oven design and operation.

2. Physical model

In the coke ovens, the coal is heated in completely sealed chambers, except for the outlets for the volatile products. These coking chambers are heated by the fuel gas burning in the channels set up on the silica brick walls of the combustion chamber. The coking chambers and combustion chambers separate one another. High temperature fume in the combustion chamber transfers heat via the wall to the coking chamber. The coal bed is heated up gradually until it is brought to a uniform temperature at which only coke remains. To guarantee the coke quality, the coal/coke bed is being heated to a temperature about 1223 K–1323 K.The raw COG flows up to the roof space over coal load, then into COG collector.

Two dimensional model of a typical 6-m-hight regenerative coke oven is schematically illustrated in Fig. 1. The coking chamber is symmetric about the midplane, as shown in the cross grid area of Fig. 1, so only half the chamber was studied. Grids were created in ICEM and exported into ANSYS FLUENT.

3. Mathematical model

To simply the mathematical model, the following hypotheses were introduced:

(1) The surface temperature of the wall was a function of only the time and it was obtained by poly-fitting on-site test data. (2) The shrinkage of coal bed during coking process was ignored.

3.1. Governing equations

General equation governing the conservation of mass, momentum, energy and species in gas phase and solid phase can be expressed as:

$$\frac{\partial}{\partial t}(\rho\phi) + div(\rho\vec{u}\phi) = div(\Gamma grad\phi) + S_\phi \quad (1)$$

where ρ is the (either solid coal/coke or gas) density in kg m^{-3}, $\vec{u}$ is the mean velocity in m s^{-1},φ is a general variable, Γ is a generalized diffusion coefficient corresponding to variable φ, S_φ is a generalized source term.

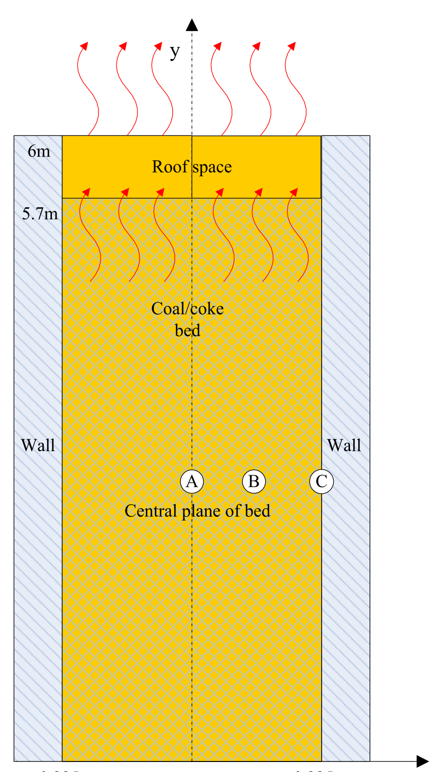

Fig. 1. Physical model of coking chamber.