The Influence of Particle Size and Swirl Intensities on Pulverized Petroleum Coke Combustion

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Abstract

To verify the effects of particle size distribution and swirl flow intensity on reaction of petroleum coke in combustion furnace, a series of numerical simulations have been carried out in this study. It was observed that as the size of particle diameter increases from 10 ㎛ to 100 ㎛, the time required for ignition was also increased from 0.04s to 1s. When the reaction phase of petroleum coke is divided into two parts, the time required for devolatilization was found to maintain almost 0.02s for all of particle diameters. But the char reaction needed longer time by the increase of particle diameters. In terms of oxidation, the temperature distribution was spatially uniform about 1600K but high temperature region are located quite differently depending on swirl number. Comparing the computed temperature with experimental temperature data, its temperature difference shows less than 10%. On the other hand, discrepancy between numerical and experimental emission data was slightly large leading to necessities of improved emission model.

Introduction

Petroleum coke, a byproduct produced from heavy crude oil residue by thermal cracking, has high heating value and low price. The world production of petroleum coke is steadily expanding due to an increasing demand for heavy oil processing. The high availability and low price of petroleum coke give us a powerful economic stimulus to be used either as the primary fuel or as the coal-petroleum coke and the oil-petroleum coke blends in a steam and power generation plant. However, petroleum coke is a challenging fuel in terms of its low volatile matter content, high carbon, sulfur and nitrogen contents, which produce high potential of undesirable emission gases such as CO_2, SOx and NOx. [1]

Due to its low volatile matter content, a number of difficulties have to be resolved to insure ignition and flame stability. Nevertheless, various technologies have been proposed in order to utilize petroleum coke in practical sector. Among them, grinding by traditional mills to obtain a powered petroleum coke is one of the useful technologies to overcome these difficulties. This approach is known to have an advantage increasing the efficiency of ignition and the flame stability of the petroleum coke for the industrial burner. [2]

Combustion process of the solid fuel like coal and petroleum coke is usually composed of moisture evaporation, devolatilization and char oxidation. After combustion of the volatile matter of the petroleum coke, subsequent oxidation of char becomes an important process to determine the flow residence time and the volume of combustion furnace. There have been many studies on the combustion of coal in research on solid fuel but studies on petroleum coke are very scare. In addition most of the studies on petroleum coke have focused on the optimization of the petroleum coke manufacturing process or improvement of coke quality. [3]

As noted above, petroleum coke has low volatile matter content and high fixed carbon content, so petroleum coke combustion characteristic is very different with coal combustion. [4] In petroleum coke combustion, one of major challenges is how to keep sufficient residence time in the furnace. The residence time is normally affected by flow conditions such as turbulent intensity. The swirling flow was used in this paper to enhance the turbulent intensity to help ensure flame stability and residence time. [5-6]

In this study a series of numerical simulations have been carried out in order to investigate the effects of particle size distribution and swirl flow intensity on reaction of petroleum coke particle and the numerical data was compared with experimental data to validate the numerical simulation as well.

2. Numerical Models

2.1 Numerical Simulation Models

The numerical simulation model is based on Semi-Implicit Method for Pressure Linked Equation Consistent algorithm using segregated solver of Ansys Fluent. Figure 1 represents the configuration of petroleum coke combustor and furnace on pilot scale (1ton/hr). The wall temperature was fixed at 1000℃ because the petroleum coke combustion operating conditions in the experimental was 1000℃. The boundary conditions were set to constant mass flow rate at the inlet and constant pressure condition at the outlet respectively.

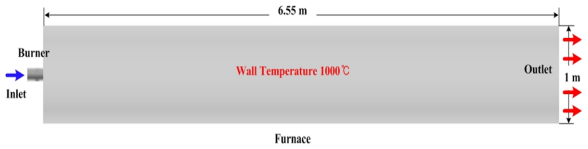

Fig.1. Schematic of numerical analysis for swirl petroleum coke combustor and furnace.

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2.2 Governing Equations

Mass conservation, momentum conservation, energy conservation, species conservation and discrete phase model (DPM) equations for reactive fluid flow are as follows:

2.2.1 Mass conservation equation

$$\nabla \cdot (\rho \vec{v}) = S_m \quad (1)$$

2.2.2 Momentum conservation equation

$$\nabla \cdot (\rho \vec{v}\vec{v}) = -\vec{v}p + \rho \vec{g} + \vec{F} \quad (2)$$

2.2.3 Energy conservation equation

$$\nabla \cdot (\vec{v}(\rho E + p)) = -\nabla \cdot \left(\sum_j h_j J_j \right) + S_h \quad (3)$$

2.2.4 Species conservation equation

$$\frac{d m_i''}{d x} = m_i'' \quad (4)$$

2.2.5 Discrete phase model equation

$$m_p \frac{du_p}{dt} = F_{drag} + F_{pressure} + F_{virtualmass} + F_{gravity} + F_{other} \quad (5)$$

3. Results and Discussions

3.1. The effect of particle diameter distribution on pulverized petroleum coke combustion

First, a combustion process of single particle was simulated in order to analyze effect of particle diameter on pulverized petroleum coke combustion. Figure 2 shows as the petroleum coke particle diameter was increased from 10 ㎛ to 100 ㎛, the time required for ignition was also increased from 0.04s to 1s. When the reaction phase of petroleum coke is divided into two parts, the time required for devolatilization was maintained almost 0.02s for all of particle diameters. But the char reaction needed much longer time for the large particle combustion.

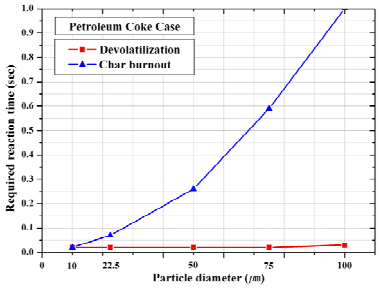

Fig.2. Comparison of devolatilization and char oxidation required reaction time at different particle size.

3.2. The effect of swirl flow intensity on pulverized petroleum coke combustion

In this study, petroleum coke combustor is a multistage burner which has two swirls at the secondary and tertiary air supply. The swirl number can be calculated

$$S_N = \frac{2}{3}\left[\frac{1-(D_{hub}/D_{sub})^3}{1-(D_{hub}/D_{sub})^2}\right]\tan\theta \quad (1)$$

where D_{hub} is the inner diameter of swirl, and D_{sub} is the outer diameter of swirl. The swirl numbers of each inlet given in Table 1 indicate that the swirl number is increased as increasing of swirl angle. Through this result we found that the swirl angle is the most effective factor on the swirl intensity.

Table 1 Swirl number with different swirl angle

Swirl angle	Inner swirl number	Outer swirl number
30	0.5295	0.5186
40	0.7695	0.7537
50	1.0929	1.0705

Figure 3 shows that the effect of swirl flow intensity on combustion furnace by the velocity vector. The corner recirculation zone is moved to the combustor side when the swirl angle increased. The high intensity of swirl in the combustion furnace makes sufficient residence time to complete the reaction of petroleum coke. Figure 4 presents the contour of temperature for different swirl angle. It was found that the temperature distribution was spatially uniform about 1600K but the position of high temperature region had quite different for each case of swirl numbers.

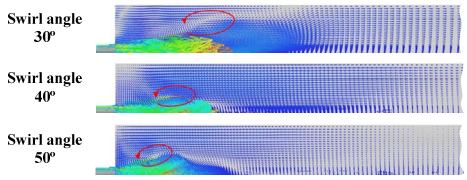

Fig.3. Velocity vector of swirl flow with different swirl angle.

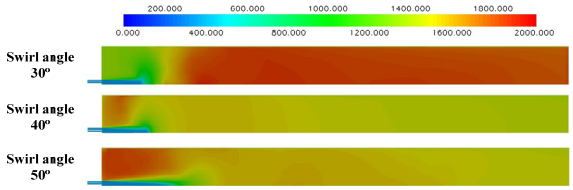

Fig.4. Contour of temperature with different swirl angle.

3.3. The validation of numerical model

To validate the numerical simulation, the numerical data was compared with experimental data. Figure 5 presents the comparison of temperature between numerical data and experimental data at the three points of the furnace. At the near burner section, the numerical and experimental temperature showed some difference, but a little bit difference at the middle and end of

furnace. Figure 6 shows the comparison of NOx, SOx emissions between numerical and experimental data. The predicted NOx emission showed good agreement with experimental data. The error was less than 30ppm. However, discrepancy between numerical and experimental SOx emission data was slightly large. Therefore, it indicated the necessities of improved SOx emission model.

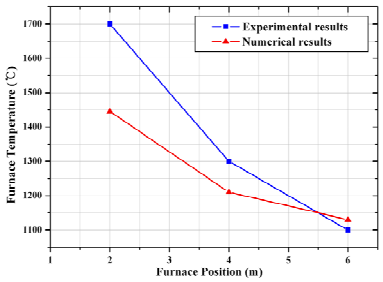

Fig.5. Comparison of temperature between numerical data and experimental data.

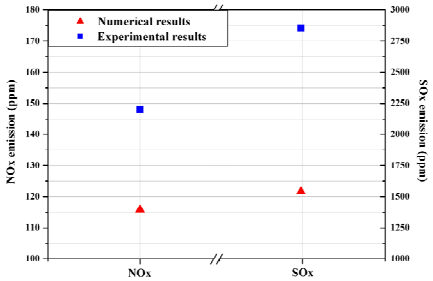

Fig.6. Comparison of emissions (NOx, SOx) between numerical data and experimental data.

4. Concluions

Petroleum coke combustion characteristics were simulated by using an Ansys Fluent commercial simulation code. Following conclusions of this work could be used for combustion design of petroleum coke boiler system.

1) The time required for devolatilization was maintained almost 0.02s at all particle diameters but the char reaction needed much longer time for larger size of particle diameter.

2) The corner recirculation zone was moved to the burner side when the swirl angle was increased. The temperature distribution was spatially uniform about 1600K but the high temperature region was located quite different. The location of high temperature region was almost same with the position of corner recirculation zone.

3) Numerical temperature data was compared with experimental temperature data and its temperature difference shows less than 10%. On the other hand, discrepancy between numerical and experimental SOx emission data was slightly large leading to necessities of improved emission model.

Acknowledgements

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