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Numerical Simulation of a Pulverized Coal Combustion Process in an Industrial Entrained Flow Reactor

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Abstract

In this study, a three-dimensional numerical simulation of an industrial entrained flow combustion reactor has been conducted. The governing equations and reactions are implemented and the operating parameters are considered according to the experimental works. The results obtained from the numerical simulation are validated by comparing with existing experimental data and similar published papers. Four different devolatilization models are investigated and the simulation results are compared to each other. The obtained results show that although the Kobayashi model has a higher calculation time, it provides more accurate results compare to the experimental data. The effect of increasing/decreasing of injected coal particle sizes are studied. The results show that increasing of the coal particle sizes from 55 to 120 μm has led to a decrease in the gas temperature inside the reactor. By reducing the average coal particle size from 55 to 30μm, the gas temperature close to the flame has increased from 1800 K to 1900 K.

Keywords: Numerical study, Combustion, Entrained flow reactor, Pulverized Coal.

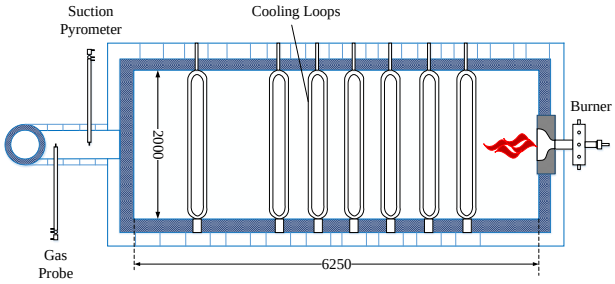
1. Introduction

Coal as a fuel plays an important role in power generation worldwide. Most of coal-fired power plants are designed to operate with pulverized-coal fuels. The pulverized coal combustion process is the key objective which is widely used in furnaces, industrial boilers, gasifiers, kilns and other energy conversion devices. Combustion process includes a set of coupled phenomena such as homogeneous and heterogeneous chemical reactions, evaporation, devolatilization, radiative and convective heat transfer, particle transport and turbulence. Typically, the powdered solid fuel particles with a specified size distribution and oxidant (pure oxygen or air) are injected inside the reactor. The process of pulverized coal combustion is a complicated phenomenon in which the maximum flame temperature may exceeds 1900 ℃. Different fluid properties such as velocity, temperature and species mole concentrations can hardly be measured experimentally in different operating conditions. In order to improve the system reliability and to enhance the design of the entrained flow reactor (EFR), the combustion mechanism and the process within the reactor need to be understood. Due to the experimental difficulties in controlling of the two-phase flow operating conditions, the combustion process is not well clarified so far. A new design of a combustion system cost a lot and may take a long period to be empirically evaluated. The computational fluid dynamics (CFD) is a well proven tool for simulating different combustion process ranging from experimental combustion devices to real scale devices. The CFD based approach can provide insight into the combustion mechanisms within the real scale devices.

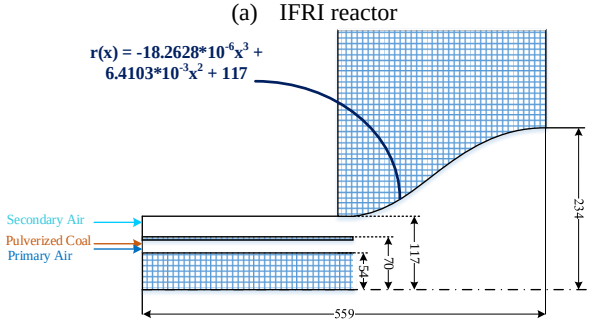
In the present study, an advanced entrained-flow coal reactor is numerically studied by considering actual operating conditions in an industrial-scale reactor. In order to explain the predicted variations in the temperature and species mole concentrations within the reactor, it is important to understand the different phenomena taking place after the coal injection. The model of entrained flow coal reactor, based on the principle of CFD is developed. Seven species transport equations are solved to gain more accurate species evaluation. The devolatilization process, homogeneous and heterogeneous reactions, radiation, heat and mass transfer as well as the interaction between the gas and coal particles are considered in this investigation. A level of confidence in the CFD simulation is conducted by studying a mesh independence test. The adopted model is first validated with the reference case and the predicted results are compared against experimental data as well as similar published study. Then, the effect of different devolatilization models as well as coal particle sizes on the combustion characteristics are evaluated.

2. Model Description and Assumptions

The current study deals with the numerical simulation of the industrial-scale 2.5 MW Flame Research Foundation (IFRF) reactor with a length of 6.25m and a square cross section of 2m × 2m as shown in Figure 1. The actual operational conditions of this reactor are given in [1]. The pulverized Gottelborn hvBb coal fuel is injected into the reactor with the primary air via the inner annular duct and the secondary air is injected via the co-axially duct around the primary duct.



(a) IFRI reactor



(b) The burner configuration

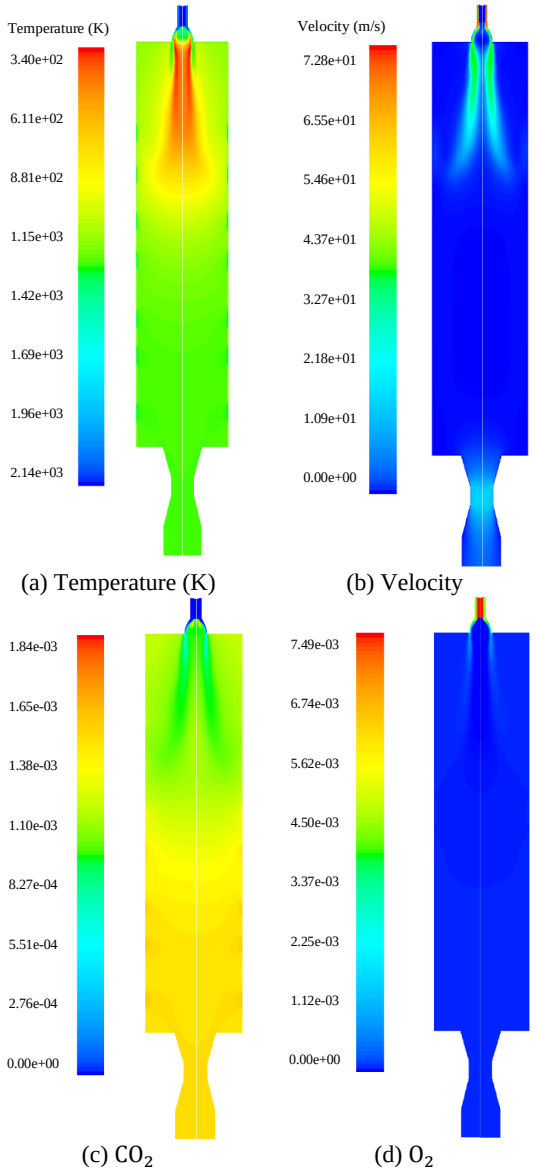
Figure 1. The schematic geometry of the (a) IFRI reactor and (b) burner (all dimensions are in mm) [1, 2]

3. Governing Equations

The Eulerian-Lagrangian method is adopted for the numerical simulation owing to the low volume loading of the particle phase in the reactor. Accordingly, steady-state, 3D time-averaged Navier- Stokes, energy and species equations are solved. The standard k-ε turbulence model is used for this simulation. The transport equations and the corresponding constants are given in [3]. In this study, seven different reactions including three heterogeneous reactions (gas-particle) and four homogeneous reactions (gas-gas) are considered. The considered reactions as well as their kinetics are extracted using the available articles [4-6] and the performance parameters are similar to the real state which are given in [1, 2].

4. Results and Discussion

Numerical simulations are conducted to explore the temperature distributions and species mole concentration within the reactor. The model is based on ANSYS-FLUENT software. In order to ensure the accuracy of the simulated model and predicted results obtained along the gasifier axis, the distribution of temperature, velocity and species mole concentrations are evaluated which are indicated in Figure 2.



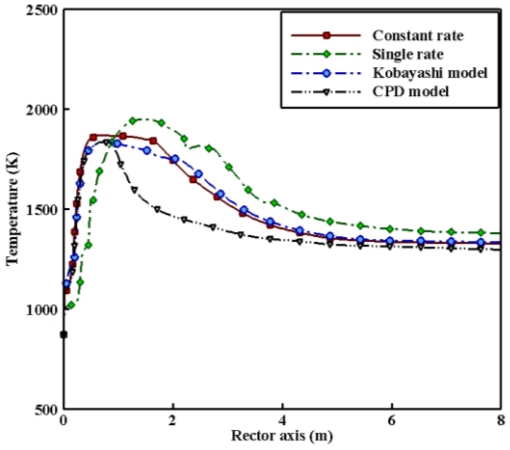
(a) Temperature (K) (b) Velocity

(c) CO_2 (d) O_2

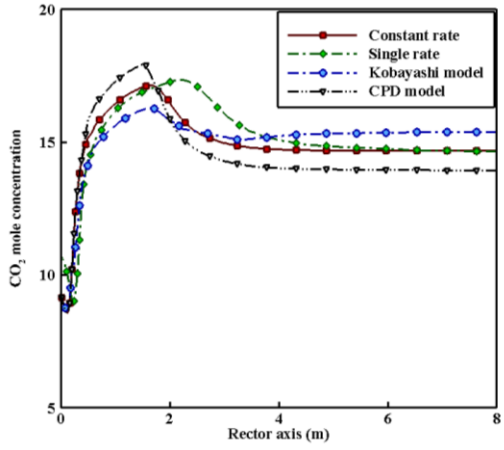
Figure 2. Contours of (a) temperature, (b) velocity, (c) CO_2 and (d) O_2 species mole concentrations on the mid-plane of the reactor

The devolatilization process is a complicated process that depends on the molecular structure of the injected fuel. The rise in the temperature of coal particles results in the release of moisture and volatile contents following the particle injection in the reactor. In the current study, the effect of devolatilization model on the combustion characteristics of a pulverized coal fuel combustion in the industrial reactor is investigated. The validated model is extended to explore the influence of four different devolatilization models including the constant rate, the single rate, the Kobayashi and the Chemical Percolation Devolatilization (CPD) models on the temperature and species distributions along the

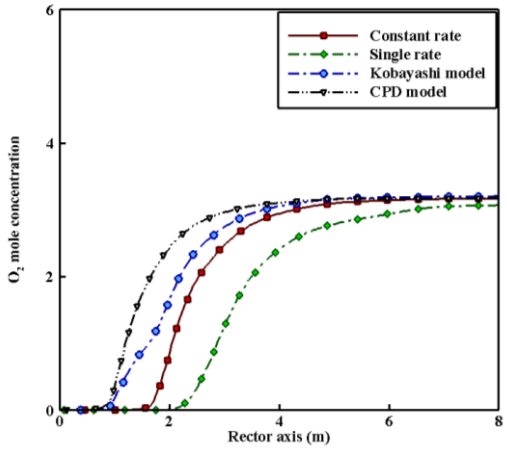
reactor. The simulation results are compared to each other as shown in Figure 3. The coal particle undergoes a series of physical and chemical process. The results showed that there is an identical trend for the four considered cases. By comparing the results obtained, it can be concluded that although there are slight differences along the axis of the reactor, there is an identical trend of temperature changes and produced gas species. For the two cases of constant rate and Kobayashi models, the temperature profiles as well as the distribution of the produced species are similar. The slight differences between the profiles along the axis of the reactor is caused to the different rates of reactions. The obtained results show that the process of devolatilization in the CPD model starts later than other devolatilization models. In other words, the devolatilization process in the CPD model starts with a delay compared to other models. Although the Kobayashi model has a higher calculation time, it provides more accurate results compare to the experimental results.



(a) Temperature



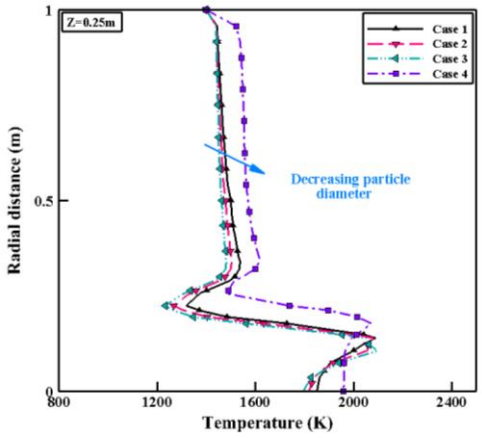
(b) CO_2



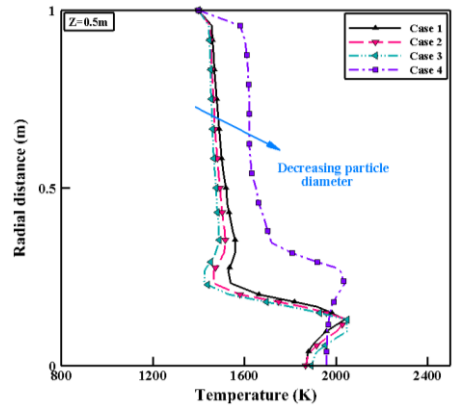
(c) O_2

Figure 3. Studying the effect of different devolatilization models on (a) temperature, (b) CO_2 and (c) O_2 mole concentrations along the axis of the reactor

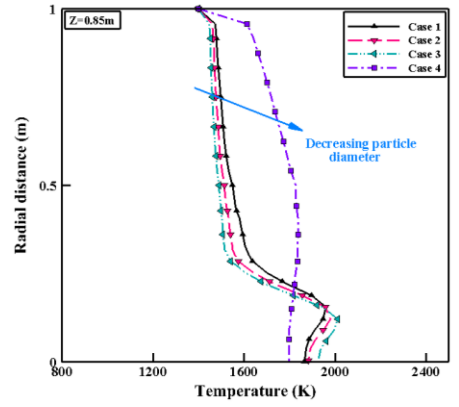
Due to the large variations may exist in the size of pulverized coal after the grinding process, the effect of coal particle size on the temperature and species mole concentrations within the reactor is numerically studied. Increasing/decreasing of injected coal particle sizes on the reactor behavior is an important issue in coal-fired power plants. In the present study, four cases are compared (Case 1 to Case 4). The particle sizes are arranged to increase from Case 1 to Case 3 in the order: Case 1 (55 μm), Case 2 (85 μm) and Case 3 (120 μm) while it is decreased in Case 4 (30 μm). The results which are given in Figure 4 show that increasing the coal particle size leads to less effective heat and mass transfer and the reactivity of coal fuel particles is decreased. Decreasing of the coal particle size has led to a faster reactivity of the particles as well as the higher gas temperature inside the reactor at the beginning of the reactor. The results show that as the coal particles move towards the end of the reactor, the rate of temperature changes is decreased and it is almost constant in the radial direction. This trend is similar for CO_2 and O_2 species concentrations.



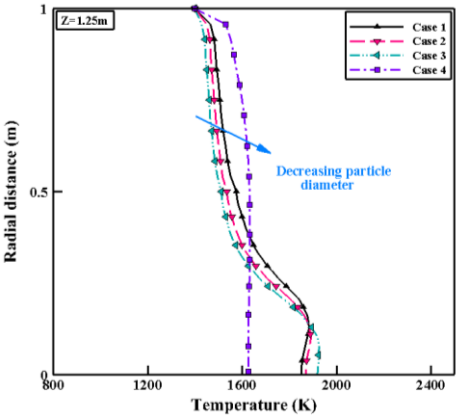
(a) Z=0.25



(b) Z=0.5



(c) Z=0.85



(d) Z=1.25

Figure 4. The effect of coal particle sizes (Case 1 (55 μm), Case 2 (85 μm) and Case 3 (120 μm) and Case 4 (30 μm)) on temperature distribution along the reactor radial distances

5. Conclusions

A numerical investigation of pulverized coal combustion is conducted for a high temperature industrial-scale reactor. The model is based on the Eulerian-Lagrangian approach which considers the mass and energy exchange between gas and solid particle phases. Different sub-models are incorporated, including heat and mass transfer, homogeneous and heterogeneous reactions, devolatilization, radiation, as well as the interactions between the gas and particle phases. The predicted results are compared against experimental data as well as similar published study. The influence of different devolatilization models on the combustion characteristics (i.e., temperature and gas species) is evaluated. The results have depicted that although the Kobayashi model has a higher calculation time, it provides more accurate results compare to the experimental data. The predicted results show that the single rate model has a maximum temperature of 1330K at the reactor exit while the CPD model has the lowest temperature of 1295K. In order to understand the effect of coal particle size on the reactor characteristics, four different particle sizes are studied. They are referred to as Case 1, Case 2, Case 3 and Case 4 with the particle mass mean diameters of 55, 85, 120 and 30 μm, respectively while other parameters are held constant. The predicted temperature and species concentration profiles along the reactor radial distances show that coal reactivity is improved by decreasing the particle size. It is observed that reducing the size of coal particles makes it easier to burn, and consequently the combustion process takes place close to the injection burner. The obtained results presented in the current study is expected to contribute to a better understanding of the process taking place inside the reactor to describe the thermochemical behavior of the coal combustion.

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