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Research Paper

Development of 3D transient wall filming mechanism during combustion by coupling Eulerian-Lagrangian approach and particle-wall interaction model

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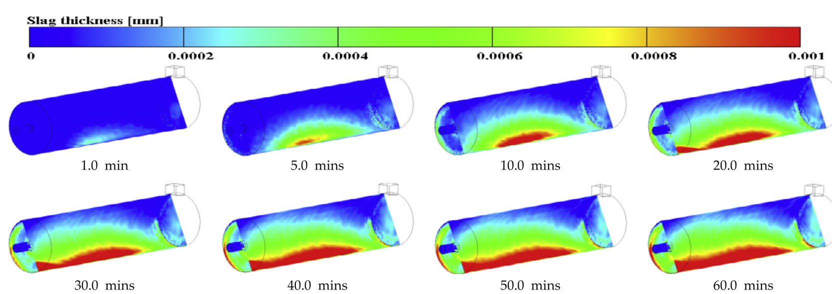
HIGHLIGHTS

- A wall filming mechanism was developed during combustion process in small furnace.
- The deposited film on the wall was found to be in good agreement with the available data.
- Slightly higher fraction of film was deposited in oxy-firing due to lower char oxidation rate.
- The deposited film thicknesses on the furnace wall were found in the range of 0–1.0 mm.
- The average molten film flows slowly due to higher viscous and surface tension properties.

GRAPHICAL ABSTRACT



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ABSTRACT

In the present study, the developments of 3D wall filming mechanism for coal combustion in a small scale furnace under air and oxy-fuel combustion conditions are presented. The principle objective of this study is to develop the film flow behavior and particle deposition characteristics on the furnace refractory wall using a commercial CFD code coupled with some user-defined sub-routines. Eulerian-Lagrangian approach of the gas-particle flow is coupled with the particle-wall interaction mechanisms including particle capturing, entrainment and wall burning sub-models. A case study has been presented to validate the model in a small scale furnace by comparing the available temperature, species data for coal-water slurry combustion and reasonable agreement has been observed. Visualization of the transient film formation and flow characteristics under air and oxy-firing cases are presented. The film thickness deposited on the refractory wall was found to be reasonably in good range with the available data. The deposited film thicknesses for both the conditions are found in the range of 0–1.0 mm. The average molten film velocity was 0.0001 m/s due to higher viscosity and greater surface tension properties. Slightly higher amount of films are formed in oxy-firing condition due to slower char oxidation rate.

1. Introduction

Slagging is a process of combustion in which ash/char particles are heated at a temperature above the fusion temperature, and then becomes molten and thus deposited along the furnace

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refractory wall. These molten particles form a layer of film called slag [1,2]. Formation of wall film is accountable for the decrease in the disposing of unused mineral content in the environment, reduced energy efficiency, broader fuel flexibility and higher percentage of low-carbon content slag residues for applications [3,4]. Also, the deposited layer of film works as a coating for the prevention of heat loss in the gasifiers. But, it reduces the overall efficiency of the plant. In order to allow slagging combustion, it is important to sustain an optimum state which requires comprehensive information about the related process and mechanisms.

In last two decades, many numerical efforts have been demonstrated for the development of coal and biomass combustion [5–9]. Only few studies were concentrated for slagging combustion [10–15]. Seggiani [16] developed a simplified model for the simulation of time varying slag flow in an entrained flow reactor. In modelling the slag formation, different physical properties such as critical viscosity, specific heat, thermal conductivity were taken into account. This 1D slag model of Seggiani [16] considered Reid and Cohen assumptions [17] and integrated with a 3D code to obtain mass deposition rate, gas temperature and heat flux. Temperature of critical viscosity is considered as an important parameter which is dependent on the composition of slag. Later, Wang [15,18] conducted another steady state model to determine the deposition and burning characteristics during firing of coal and wood. In this model, Particle impingement and particle sticking characteristics are applied by using Wood's [19] and Walsh's [20] mechanisms. The specialty of this model is the wall burning and slag flow process, but only limited for molten slag modelling. Compared to Seggiani's model [16], this Wang model reflects the wall burning phenomenon when fuel particles are stuck on the slag surface and its consequence on char oxidation and heat transfer performance. But both of the model cannot determine the slag behavior in others direction. Yong [21,22] developed a steady state model to describe the flow and heat transfer characteristics in slag layer of solid fuel gasification by combining the model developed by Seggaini [16] and Wang [15,18] as described earlier. In this modelling, an updated temperature profile is assumed replacing Seggaini's assumptions [16]. Bockelie [23] and Chen [24] extended the 1D slag model into the 2D wall surface in fuel combustor. But slag flow is considered in one direction only. This 2D method considers the spatial distribution of ash particle deposition. This approach cannot completely solve the 3D flow behavior. Liu and Hao [25] modeled a two dimensional slag flow in an entrained flow gasifier using the volume-of-fluid (VOF) model. Ni [12] used the same technique to model the multiphase multilayer slag flow and phase transformation considering two-dimensional mesh with uniform ash deposition rate.

Most of the above studies on modelling of slagging are based on 1D and 2D modelling. Only few studies attempted for 3D modelling. Chen [26] developed a comprehensive slag flow model to determine the slag behavior during coal combustion and gasification in a 5 MW pressurized combustor. This model integrated different models for fluid and particle trajectories modelling implemented in a commercial CFD code. This model completely decides the 3D features of char/ash deposition, slag flow, as well as heat transfer through the slag layer. The result showed that 1–2 mm slag layer is formed on the refractory wall which is basically molten. The mean slag flow rate is normally about 0.1 mm/s. The relationship between the slag thickness and slag velocity, heat flux and slag temperature are presented in the numerical work of [15]. It is observed that slag velocity decreases with the increase of slag thickness. Similar trend is observed in the study of Chen [26].

As modelling of wall filming during coal combustion has shown limited progress in the literature compared to other conventional combustion processes [2], hence, the foremost goal of the present study is to develop a comprehensive 3D wall filming mechanism considering particle capturing, entrainment and wall burning sub-model in a small scale furnace using CFD technique. Also, to examine the factors associated with the particles deposition characteristics that experience between combustion and wall filming-called film wall interactions are important. In order to validate the model, a 5 MWth coal water slurry furnace under air and oxy-firing conditions is considered to identify the filming behavior and related combustion issues. Also, this study looks at the effects of different species level (O_2, CO_2, H_2O, CO) and thermal and flow behavior under selected conditions using a commercial CFD code coupled with required user-defined subroutines.

2. Development of the model

An understanding and fundamental knowledge in modelling of wall filming is important for predicting the particles deposition, conversion into film thickness and related heat transfer issues. In general, the modelling of wall filming consists of several complexes and simultaneous processes such as the film flow, particle capture and particle consumption modelling. After the gas-particle phase, some of the fuel particle hits the refractory wall of the furnace, some of the particles are captured and some of the particles are rebound from the wall based on the capturing criteria in wall-particles interaction phase. In modelling of filming, gas and film flow are treated as separate single phases. So this is not a complete two-phase model but rather two single phase models attached at the film surface. The coupling of the two phases is achieved by a modified set of boundary conditions based on semi-empirical relations. It is assumed that the film thickness is very small in relation to the particle size of the gas flow which is one of the main limitations of wall filming modelling. Therefore, no adaptation of the volume grid to the wall film surface is necessary. The detailed structure of the wall filming model by combining solid-gas phase and particle-wall interaction is presented in Fig. 1.

2.1. Combustion modelling

In gas phase modelling, 3D non-steady state Eulerian partial differential conservation equations are considered for multicomponent gaseous phase. The general form of Eulerian transport equation used in the present computation is [27,28]:

$$\frac{\partial}{\partial t}(\rho\phi) + \frac{\partial}{\partial x_i}(\rho U_i \phi) = \frac{\partial}{\partial x_i}\left(\Gamma \frac{\partial \phi}{\partial x_i}\right) + S_\phi + S_{p\phi} \tag{1}$$

In particulate Phase model, discrete droplet method (DDM) [29–32] is considered. This method includes the momentum exchange, heat and mass transfer phenomena. The differential equation for a solid particle is defined as follows where the coefficient are given in [33]:

$$m_p \frac{du_{id}}{dt} = \vec{F}_{idr} + \vec{F}_{ig} + \vec{F}_{react} \tag{2}$$

$$\text{where} \quad \vec{F}_{idr} = \frac{1}{2} \cdot \rho_g \cdot A_p \cdot C_D \cdot |u_{rel}| \cdot u_{rel} \tag{3}$$

$$\vec{F}_{ig} = V_p \cdot (\rho_p - \rho_g) \cdot g_i \tag{4}$$

$$\vec{F}_{react} = V_p \cdot \left(\frac{-m_{vp}}{dt}\right) \tag{5}$$

Eddy Breakup (EBU) model, one of the important turbulence controlled combustion model is applied for the combustion modelling. This model was first introduced by Spalding [34] and modified later by Magnussen and Hjertager [35]. This model