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Research article

The influence of swirling flows on pulverized coal gasifiers using the comprehensive gasification model

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ABSTRACT

The burner swirl intensity plays an important role in membrane wall safety and the gasification performance of pulverized coal, swirl gasifiers. The comprehensive gasification model (CGM), having two reaction regions and one radial heat transfer region, was used to simulate the influence of the swirl number (SN) on gasification performance, multiphase flow, reactions in the space, and reactions regarding the membrane wall. The results show that an SN of 0.66 is a critical point to divide low-swirl and high-swirl flows for the single-swirl-burner gasifiers of this study. Gasifier performance increases sharply with increased SN for low-swirl burners, whereas SN has little influence on gasifier performance (and multiphase flow) for high-swirl cases.

In this paper, we examine the relationship between burner swirl and flow fields, temperature distributions in the space and on membrane wall, slag thickness, and the molten slag velocity distribution on the membrane wall. The influence of SN on these parameters is more remarkable at the top of the reattachment point than below it. The slag layer formed on the membrane wall isolates high-temperature gas effectively, except around the reattachment point. To guarantee gasifier performance and membrane wall safety, the burner SN should be between 0.66 and 0.9 for the single-swirl-burner gasifiers of this study.

1. Introduction

Confined swirl flow is important and widely used in energy production devices such as gas turbine combustors, internal combustion engines, industrial burners, and boilers. In combustion systems, swirl-flow burners are essential owing to their significantly shortened the flame length, flame stability, combustion intensity, and combustor performance in comparison with non-swirling burners.

Entrained-flow coal gasification technology is widely used in China owing to its high conversion ratio and low pollution output. Some entrained-flow coal gasification technologies, such as GSP (a gasification technology of Siemens), HT-L (a gasification technology of China Aerospace Science and Industry Corporation), and SHELL (a gasification technology of Shell Globe), utilize a special geometric configuration for the burner (or reactor) to achieve a swirl flow field within the gasifier [1]. The GSP and HT-L gasification technologies use a top-setting, single-swirl burner (SSB) gasifier.

In a confined swirl-jet reaction flow, the swirl affects jet growth, flame shape, flame size, combustion stability, and intensity. All these effects are largely dependent on the degree of swirl imparted to the flow, generally known as the "swirl number" (SN) [2]. The SN can be defined as:

$$\mathrm{SN} = \frac{1}{d/2}\frac{\int_0^{d/2}\rho\omega u r^2 dr}{\int_0^{d/2}\rho u^2 r dr} \tag{1}$$

where u, ω, and d are the axial velocity, the tangential velocity, and the upstream tube diameter, respectively. In commercial SSB gasifier operation, a common accident is the burn-through of the membrane wall at the top of the gasifier. According to gas-particle reaction and flow field research, when a swirl-jet flame of high-temperature is used in SSB gasifiers, the swirl-jet flame extends to the membrane wall, where the temperature at the end of the flame is higher than the outlet temperature [3]. Operational adjustments have been tried to eliminate this high-temperature region, including changes to operational loading, oxygen-coal ratio, operational pressures, and coal properties [4]. It has been found that the shape and temperature distribution of the flame depend strongly on the SN. The high-temperature membrane region disappears with a commensurate and reasonable decrease in the SN. However, the carbon conversion (defined as the ratio of the carbon in coal conversion into gas phase) of the gasifier also significantly

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decreases.

Industry operational tests have shown that swirl intensity has a contradictory influence on membrane wall safety and gasification performance. Therefore, there is a necessity to investigate the swirl intensity in the multiphase reaction flow and heat transfer within SSB gasifiers. With the rapid advancement of computational fluid dynamics (CFD), modeling and simulation are readily available for the study of complex, two-phase reactions, and flow processes in different gasifiers [5–7]. For SSB gasifiers, this modeling work is uncommon compared with pulverized-coal swirl combustors [8–10]. Bi et al. [11] developed a 3-D numerical model to simulate GSP gasifiers with different SNs. They found that the carbon conversion of GSP gasifiers linearly decreased with SN, and approximately 2–20% of particles flowed directly out of the gasifier without recirculating or colliding with the membrane. We previously proposed a comprehensive gasification model (CGM) to model SSB gasifiers [12]. The detailed information about the flow field, temperature distribution, particle residence time distribution, and membrane wall reaction time distribution were discussed. Till now, the influence of the swirl jet number on the molten slag flow, wall reactions, and heat transfer has not been systematically investigated.

In this study, we use the CGM model to investigate the slag flow, phase transformation characteristics, and heat transfer to the membrane wall, as well as discuss the influence of SN on multiphase flow and reaction processes.

2. Description of the CGM model [12]

In an entrained flow gasifier, there are several complicated physical and chemical multiphase processes occurring in the space and on the membrane wall. These processes include gas-particle two-phase flow, moisture evaporation, coal de-volatilization, heterogeneous reactions, homogeneous reactions, slag surface reactions, slag phase transformations, molten slag flow, and heat transfer. According to the characteristics of these processes, the gasifier can be divided into two reaction regions, and one heat transfer region. Fig. 1 illustrates the three-region distribution within the membrane wall and the physical space of an entrained flow gasifier using the CGM model. The gas-particle flow and reaction area (region *I*) is located at the gasification chamber, where the gas phase turbulent flow, particle dispersion, coal particle processes (physical and chemical), and heat transfer processes occur. Region *II* is located at the surface of the molten slag and includes particles deposition and the wall reaction region. There are molten slag layer, solid slag layer, SiC refractory layer and metal wall in the region *III*, which refers to the molten-slag laminar flow and the heat transfer through the membrane wall. The SiC layer is lined on the surface of the metal wall and used to resist corrosion, thermal shock and abrasion of the hot gas and molten slag. As show in discussion section, the temperature gradient in the vertical direction $(T_{o,\ i} - T_{w,\ i})/\delta_i$ is much greater than

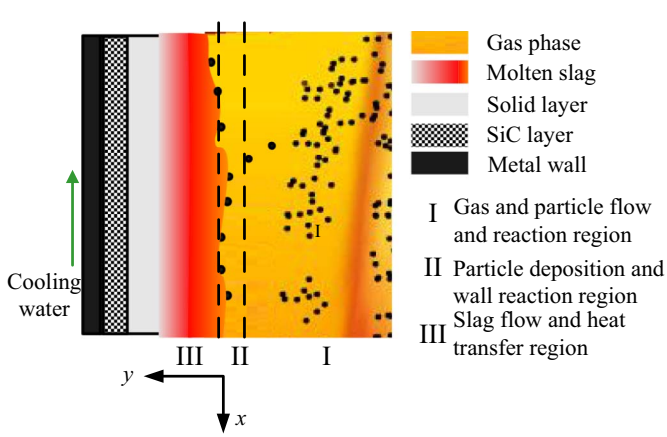

Fig. 1. Illustration of the three regions in the CGM model.

temperature gradient in the axial direction $(T_i - T_{i-1})/\Delta x$. Thus, we can assume that the heat transfers in the vertical direction.

Until now, most modeling studies for entrained flow gasifiers have focused on region *I* [3,5–7,11,13] or both region *I* and region *III* [14–17]. The detailed processes within region *II* (the particle deposition and wall reaction region) have not yet been considered, although it is important for the modeling of entrained flow gasifiers. This region not only provides more accurate boundary conditions for the models of regions *I* and *II*, but also ensures more precise gasifier performance of simulations, particularly for the examining carbon conversion and carbon residue in the slag.

For a commercial gasifier, it is operating smoothly for most of time, and our research focus on the multiphase flow in a stable operating gasifier. So the complicated and dynamic physical and chemical multiphase processes occurring in the space and on the membrane wall can be simplified as steady-state processes. In region *I*, the time-averaged steady-state Navier-Stokes equations are solved. An appropriate turbulence model is used to close the Reynolds-averaged Navier-Stokes (RANS) equations. With the energy conservation and gas species transport equations solved, the particle stochastic trajectory model, which describes turbulence-particle interactions, is formulated based on the instantaneous governing equations for particle energy, mass, and momentum [11–14]. A pair of parallel, first-order, irreversible reactions are used to simulate the de-volatilization process [12–14]. Simple global reactions involving gaseous combustion, water-gas shift, and methane-steam reactions are considered, and the eddy dissipation concept (EDC) model is used to simulate the interaction between turbulent flow and the reactions [12,14,18]. The char reaction with CO_2, H_2O, and O_2 is modeled using a random pore model, in which the kinetic reaction control regime, and pore and film diffusion regimes are included [19–20]. In the CGM, the particle size and density evolution with the char conversion are modeled.

In region *II*, sub-models are used to describe the particle deposition process and the reaction of combustible components in trapped particles on the membrane wall. In the particle deposition model, the interaction between coal/ash particles and the membrane wall can be defined as follows: a reflection or deposition, based on the viscosity and temperature of particle/wall surface [16], as shown in Table 1. T_{cv} is the temperature of critical viscosity, which is the key parameter to characterize the slag flow ability. It is recognized as a sharp break in the viscosity versus temperature curve [21]. We_{cr} is the critical Weber number at the setting values of 1, and C_{cr} is the critical carbon conversion at the setting value of 0.88 in this study [22]. The particle deposition rate (m_{in}) can be defined as

$$m_{in} = \sum_{p=1}^{N_{trap}} \frac{m_p}{A_{face}} \tag{2}$$

where N_{trap} is the number of the trapped particle; m_p is the mass of the trapped particle, and A_{face} is the area of the cell face at the wall.

For trapped particles, most studies have assumed that the deposited-particle reaction rate is slower than the particle's reaction rate in the space, owing to the "reduced submerged particle external surface model" and slower diffusion of gas phase. In the CMG wall reaction model, trapped particle reaction rates $R_{w,\ j}$ are higher than the particle's reaction rate in the space, with a promotion factor of approximately 2 [23]. The wall reaction time ($t_{w,\ p}$, s) is described by the trapped particle submerge time. The wall reaction model can be defined as [12]

$$R_{w,j} = C_0 R_j \begin{pmatrix} t < t_{w,p}, & C_0 = 2 \\ t \geq t_{w,p}, & C_0 = 0 \end{pmatrix} \tag{3}$$

$$t_{w,p} = d_p/(m_{in}/\overline{\rho_{dr}}) \tag{4}$$

where R_j is the normal particle reaction rate, which is calculated with the heterogeneous char reaction rate function in region *I*; t is the trapped particle react time, s; C_0 is reaction rate promotion factor, and