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Characterization of high-turbulence zone in slowly moving bed slagging coal gasifier by a 3D mathematical model

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ABSTRACT

A slowly-moving bed slagging coal gasifier (SMB gasifier) is developed for utilizing those largely-reserved coals with high ash fusion temperature (>1500 °C). Mathematical modelling is regarded more effective than experimental studies to understand and optimize the performance of the gasifier at industry scale. In this paper, a three-dimensional (3D) computational fluid dynamics (CFD)-based mathematical model has been developed to study the shape and size of the so-called high-turbulence zone in the SMB slagging coal gasifier. Reynolds number and volume fraction of solid phase are used to define the boundary of high-turbulence zone, with their critical values 250 and 0.6, respectively. The influences of gasifying agent velocity and coal particle size on the shape and size of the high-turbulence zone are also investigated. The simulation results indicate that with the increase of coal particle size and gasifying agent velocity, the shape of high-turbulence zone is changed from boot-shape to arch-shape, and the slugging in the upper part of the gasifier is confirmed.

1. Introduction

Coal gasification technology is considered as one of the most effective clean coal technologies. Fixed bed gasification is widely applied due to its simple structure and low costs, especially in China [1]. Until late 2014, the proven reserves of coal in China are around 1.5 trillion tons and ranks the third in the world [2]. However, because of more than half of the coals are high in ash ($A_d > 40\%$), high in sulfur ($S_t > 2\%$) and high at ash fusion temperature (>1500 °C) [3], the slag blockage in the fixed bed gasifier occurs frequently and brings about adverse impact on life-length and stable running. The melting point of ash can be reduced significantly with the addition of fluxing agent such as CaF_2, but this leads to problems such a heat loss and harmful fluorine gas generation. Recently, the called slowly-moving bed slagging coal gasifier (SMB gasifier) was developed for utilizing such coals with high ash fusion temperature in China, as shown in Fig. 1. The SMB slagging coal gasifier consists of two parts. The upper part is a slowly-moving bed for coal drying, devolatilization, gasification and combustion of coals, while the lower part is a slag bath where the ash is melted with supplement heat produced by the reaction of oxygen and syngas. In the SMB gasifier, the coal is introduced from the top and the molten slag is discharged smoothly from the bottom. At the base of the gasifier, gasifying agents (usually mixture of steam and oxygen) are injected through tuyeres into the combustion zone where high temperature is required to melt the ash and to provide heat to drive the gasification reactions.

The operation of SMB gasifier is similar to the so-called ironmaking blast furnace (BF) in steel industry [4]. In the BF, hot air blast (>1200 °C) is injected at high velocity at the lower part of the BF through tuyere, leading to a cavity zone in coke packed bed. This cavity zone is termed raceway in ironmaking BF [5–8]. Similarly, there also exists a cavity zone around the combustion zone at the low part of SMB gasifier. This cavity zone is termed high-turbulence zone in the SMB gasifier. The efficient operation of SMB gasifier depends mainly on heat supply from the high-turbulence zone to the whole bed for drying, pyrolysis, chemical reaction and ash melting. Furthermore, the generation and transport of heat is determined by the entrainment of coal particles and the extent of its burning in the high-turbulence zone, which in turn are greatly dependent on the shape and size of the high-turbulence zone. In addition, the shape and size of the high-turbulence zone are significant for the slag bath design and burner design. Therefore, characterization of the high-turbulence zone is necessary and the influences of key operational conditions on the shape and size of high-turbulence zone are essential. Compared to experimental studies at lab- or pilot-scales, mathematical modelling is a cost-effective method for understanding in-furnace phenomena especially under the conditions of high temperature and high pressure, and furthermore, 3D modelling provides good insight into information necessary for practical problems.

In the past, most models of fixed bed gasifiers were used to study the effects of different parameters on the composition of raw product gas and temperature distribution inside the gasifier. Zero-dimensional

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models were developed to evaluate the compositions of raw product-gas by assuming the thermodynamic equilibrium [9–11]. One-dimensional steady-state models were developed by considering the variations of physical and chemical properties along the height of the reactor [12–14]. Most of the 2D models, in turn, were used to simulate gasification process in fluidized-bed or entrained flow bed gasifier [15–18]. To date, three-dimensional models have not been reported in the open literature for fixed bed gasifier or slowly-moving bed gasifier. On the other hand, many papers on the raceway zone in BF can be used as references for the present work. Most modelling were based on Eulerian-Eulerian approach [5,19–20] or Eulerian-Lagrangian approach where solid phase motion is described by discrete element method (DEM) [6–7,21–22]. In addition, some scaled-down cold models of BF in laboratory were also used to study the raceway zone [23]. To date, no specific 3D modelling works have been reported in the literature for SMB slagging coal gasifier.

In this work, a 3D mathematical model is developed for describing multiphase flows in the slowly moving bed slagging coal gasifier. It is used to characterize the high-turbulence zone in terms of shape and size. The motion of gas and solid phases are solved using a Eulerian-Eulerian multiphase approach with exchange terms for the mass and momentum. The influences of some key variables such as gasifying agent velocity and coal particle size on the shape and the size of high-turbulence zone are investigated. The model is developed based on a commercial software ANSYS FLUENT with user defined functions.

2. Model description

The SMB gasifier is a vertical cylindrical reactor. The computational domain includes tuyere, high-turbulence zone and coal bed.

2.1. Assumptions

- Gas and solid phases are solved as interactive continuum phases in a Eulerian-Eulerian multiphase flow framework;
- Gas phase is considered as incompressible ideal gas. Solid phase is treated as a continuum phase with constant density;
- Coal particles are regarded as smooth, inelastic and spherical.
- Isothermal flow conditions are assumed without chemical reactions considered. The combustion of the coal does not increase the pressure inside the high-turbulence zone, and so the combustion is not expected to change the high-turbulence zone. Therefore an isothermal solution is sufficient for characterizing the high-turbulence zone.

2.2. Governing equations

2.2.1. Continuity equations

Continuity equation for a phase q is

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q\right)+\nabla\cdot\left(\alpha_q\rho_q\vec{u}_q\right)=0 \tag{1}$$

$$\sum\alpha_q=1 \tag{2}$$

where α_q is the volume fraction of phase q, ρ_q is density of phase q (kg/m^3) and $\vec{u}_q$ is velocity of phase q (m/s).

2.2.2. Momentum equations

Conservation equations of momentum for gas phase are

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g\vec{u}_g\right)+\nabla\cdot\left(\alpha_g\rho_g\vec{u}_g\vec{u}_g\right)=-\alpha_g\nabla p+\nabla\cdot\bar{\bar{\tau}}_g+\alpha_g\rho_g\vec{g}+K_{sg}\left(\vec{u}_s-\vec{u}_g\right) \tag{3}$$

$$\bar{\bar{\tau}}_g=\mu_{\mathrm{eff},g}\left(\nabla\vec{u}_g+\nabla\vec{u}_g^{\,T}\right)-\frac{2}{3}\left(\mu_{\mathrm{eff},g}\left(\nabla\cdot\vec{u}_g\right)\bar{\bar{I}}+\rho_g k_g\right)-P_g\bar{\bar{I}} \tag{4}$$

$$\mu_{\mathrm{eff},g}=\mu_g+\mu_{t,g} \tag{5}$$

Conservation equation of momentum for solid phase is

$$\frac{\partial}{\partial t}\left(\alpha_s\rho_s\vec{u}_s\right)+\nabla\cdot\left(\alpha_s\rho_s\vec{u}_s\vec{u}_s\right)=-\alpha_s\nabla p-\nabla p_s+\nabla\cdot\bar{\bar{\tau}}_s+\alpha_s\rho_s\vec{g}+K_{gs} \tag{6}$$

where $K_{gs}=K_{sg}$. The Gidaspow [24] model is adopted to solve the coefficient.

$$K_{sg}=\begin{cases}150\dfrac{\alpha_s(1-\alpha_g)\mu_g}{\alpha_g d_s^2}+1.75\dfrac{\rho_g\alpha_s|u_s-u_g|}{d_s} & \alpha_g\le 0.8\\ \dfrac{3}{4}C_D\dfrac{\alpha_s\alpha_g\rho_g|u_s-u_g|}{d_s}\alpha_g^{-2.65}C_D=\dfrac{24}{\alpha_g\mathrm{Re}_s}\left[1+0.15(\alpha_g\mathrm{Re}_s)^{0.687}\right] & \alpha_g>0.8\end{cases} \tag{7}$$

For granular flow in the compressible regime (i.e., the volume fraction of the solid phase is less than its maximum permitted value), the pressure of solid phase is calculated independently and used in the pressure gradient term ∇p_s in the granular-phase momentum equation. Because one Maxwellian velocity distribution is used for the particles, one granular temperature is introduced into the model for the solids pressure and viscosities. The solids pressure is composed of a kinetic term and a second term due to the particle collision.

$$p_s=\alpha_s\rho_s\left[1+2(1+e_{ss})\alpha_s g_{0,ss}\right]T_s \tag{8}$$

where e_{ss} is the restitution coefficient for particle collision, $g_{0,ss}$ is the radial distribution function.

$$g_{0,ss}=\left[1-\left(\frac{\alpha_s}{\alpha_{s,\max}}\right)^{\frac{1}{3}}\right]^{-1} \tag{9}$$

and T_s is the granular temperature (m^2/s^2), which is proportional to the kinetic energy of the particle motion fluctuation. The transport equation derived from kinetic theory takes the form.

$$\frac{3}{2}\left[\frac{\partial}{\partial t}(\alpha_s\rho_s T_s)+\nabla\cdot\left(\alpha_s\rho_s\vec{u}_s T_s\right)\right]=-\left(p_s\bar{\bar{I}}+\bar{\bar{\tau}}_s\right):\nabla\vec{u}_s-\frac{12(1-e_{ss}^2)g_{0,ss}}{d_s\sqrt{\pi}}\rho_s\alpha_s^2 T_s^{\frac{3}{2}}-3K_{gs}T_s \tag{10}$$

where $\bar{\bar{\tau}}_s$ is the solid stress tensor (Pa) and is expressed as

$$\bar{\bar{\tau}}_s=\alpha_s\mu_s\left(\nabla\vec{u}_s+\nabla\vec{u}_s^{\,T}\right)+\alpha_s\left(\lambda_s-\frac{2}{3}\mu_s\right)\nabla\cdot\vec{u}_s\bar{\bar{I}} \tag{11}$$

The solid stress tensor contains the shear μ_s (Pa·s) and bulk viscosities λ_s(Pa·s) is from particle momentum exchange due to translation and collision motions.

The collisional [23], kinetic and frictional parts are added to describe the solids shear viscosity

$$\mu_s=\mu_{s,\mathrm{collision}}+\mu_{s,\mathrm{kinetic}}+\mu_{s,\mathrm{friction}} \tag{12}$$

$$\mu_{s,\mathrm{collision}}=\frac{4}{5}\alpha_s\rho_s d_s g_{0,ss}(1+e_{ss})\left(\frac{T_s}{\pi}\right)^{1/2}\alpha_s \tag{13}$$

$$\mu_{s,\mathrm{kinetic}}=\frac{\alpha_s d_s\rho_s\sqrt{T_s\pi}}{6(3-e_{ss})}\left[1+\frac{2}{5}(1+e_{ss})(3e_{ss}-1)\alpha_s g_{0,ss}\right] \tag{14}$$

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