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Full Length Article

Comprehensive model with time limited wall reaction for entrained flow gasifier

Jianliang Xu, Qingfeng Liang, Zhenhua Dai, Haifeng Liu *

Key Laboratory of Coal Gasification and Energy Chemical of Ministry of Education, East China University of Science and Technology, P.O. Box 272, Shanghai 200237, PR China
Shanghai Engineering Research Center of Coal Gasification, East China University of Science and Technology, P.O. Box 272, Shanghai 200237, PR China

HIGHLIGHTS

- A comprehensive model with time limited wall reaction has developed for simulation of the entrained-flow gasifier.
- An industrial single swirling burner gasifier has been studied.
- Average fly time in the spatial space and wall reaction time on the membrane wall of the particle have been calculated.

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ABSTRACT

A comprehensive model with time limited wall reaction was developed for the simulation of complex gas particle molten slag three-phase reactions and flow processes in an entrained flow gasifier. Promotional conversion rate, wall reaction time and particle size/density evolution have been considered in the wall reaction model. In order to validate the proposed model, an industrial single swirling burner gasifier was simulated, and the gasifier performance, residual carbon ratio in the trapped particle and fly ash are compared with experimental measurements. The comparison results indicate that the proposed model has sufficient accuracy for entrained flow gasifier simulation. In a single swirling burner gasifier, approximately 55.4% of the coal particles fed from the swirling burner are trapped by the molten slag surface, and 22.5% of carbon in the trapped particles are converted during the wall reaction process. The detailed residence time of the trapped particle has been calculated; the average fly time of the particle before trapped is approximately 0.66 s; and the average wall reaction time on the membrane wall is approximately 3.55 s.

1. Introduction

Coal is the most important energy resource in China due to the abundance of deposits. Traditionally, coal is used directly for combusting, which causes numerous environmental problems. Therefore, developing technology that converts coal into energy and chemical products in a clean and efficient way has attracted extensive attention. Entrained flow coal gasification technology is a clean and highly efficient conversion process that plays a highly important role in coal utilization processes, such as chemical industry, integrated gasification combined cycle (IGCC) systems and polygeneration plants. According to the feed stock status, entrained flow coal gasification technology can be classified into coal water slurry (CWS) gasification technology and pulverized coal (PC) gasification technology. The pulverized coal membrane wall-lined entrained flow gasification technology is ideally suited for coal with high ash fusion temperatures and ash content in comparison with CWS gasification technology. Various pulverized coal gasification technologies have been developed, such as GSP, HT-L and SHELL [1,2].

In an entrained flow gasifier, the combustible components are converted into the gas phase, and the mineral content is converted into ash. Most of the ash particles or droplets are deposited on the refractory or membrane wall and form a slag layer that flows down to the quenching system (to form coarse slag). Therefore, the multiphase flow and reaction processes in the interior space and membrane wall of the gasifier have direct influence on the gasifier's performance and safe and stable operation. Due to the high temperature and pressure operation conditions, it is highly difficult to obtain detailed information, even by the most advanced testing instruments in the commercial operation of an entrained flow

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* Corresponding author at: Key Laboratory of Coal Gasification and Energy Chemical of Ministry of Education, East China University of Science and Technology, P.O. Box 272, Shanghai 200237, PR China.

E-mail address: hfliu@ecust.edu.cn (H. Liu).

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Nomenclature

A, A_m	area facing the adjacent cell
a, b	coefficients of thermal conductivity of slag
$C, C_{p,c}$	heat capacity of the slag and cooling water
C_0	reaction rate promotion factor
C_{sw}	swelling ratio
d_p	diameter of the particle
d_{Ch}	diameter of char particle
$F_{m,c}$	flow rate of the cooling water
$f_{v,0}, f_{w,0}$	moisture and volatile mass fraction of parent coal particle ns
h_c	convection coefficient of the coolant
k_s, k_r, k_m	thermal conductivity of slag, SiC and tube
k_1, k_2	coefficients of thermal conductivity of SiC refractory
L	width of the control volume
m, n	coefficients of molten slag viscosity
m_{ex}	out-flow rate of molten slag
$m_{in}, m_{w,r}$	particle deposition rate and char consumption rate
m_p	parent mass
m_C, m_{Ch}	mass of carbon and char particle
q_{in}	heat flux from the gas phase
q_{out}, q_m	heat flux through the slag and refractory layer
$q_{ex,i}$	heat transfer rate with the out flow of molten slag
$R_{w,j}, R_j$	stuck and normal particle reaction rate heterogeneous reaction
X	carbon conversion ratio
X_A	ash mass fraction in the char particle
T_{cv}	temperature of critical viscosity
T_o, T_w	slag and refractory surface temperature
T_{in}	temperature of particle deposited particle
T_c	cooling water temperature
$t_{w,p}$	wall reaction time
v	velocity of the molten slag
α	empirical mode of burning parameter
β	lean angle of the membrane wall
η_s	slag viscosity
ϕ	fraction of solid slag
ρ	slag density
$\delta_{l,i}, \delta_{s,i}, \delta_i$	thickness of molten, solid and total slag
δ_m, δ_r	thickness of tube and SiC
τ	shear stress
ρ_A	ash density
ρ_{Ch}	char particle density

gasifier. With the rapid advancement of computational fluid dynamic (CFD) technology, modeling and simulation methods have been widely used studying the complex multiphase reactions and flow processes in the gasifier. To date, most of the modeling of the entrained flow gasifier includes two parts: the gas-particle/droplet flow and reaction processes and the slag flow and heat transfer processes. The two processes are coupled with mass, momentum and heat transfer. Among these factors, the interactions between the coal/ash particles and refractory wall or membrane wall are highly important for the two processes. In the majority of gas-particle/droplet flow and reaction numerical simulations, the slag layer is treated as a solid wall and the particle rebounds when it impacts the solid wall [3–6]. However, in the slag flow and heat transferring process predicted works, the interaction between the coal/ash particles and membrane wall can be defined as reflection or deposition based on the coal/ash critical viscosity or particle/wall temperature [7–9]. According to experiments in the slag tap gasifier, most of the ash particles are captured when they touch the molten slag wall, and it is notably difficult for them to return to space [10]. If these particles contain combustible matter, they will continue to react with gas phase and flow with the running molten slag. Wang [11,12] had proposed a fundamental model to describe the trapped particle wall burning process of a combustion furnace. Several studies [13,14] were carried out to model the trapped particle reaction on the surface of the slag layer based on Wang's model. All of these studies assumed that the wall reaction is a slower char reaction due to the slow diffusion of the gas phase or reduced submerged particle external surface. However, in our recently experiment [15], it was found that the gasification rate of char on the molten slag is promoted in comparison with the char reaction.

Another assumption of current studies is that the submerged particle will stay on the surface of the molten slag during the wall reaction process. In the entrained flow gasifier, the flow velocity of molten slag is smaller than 5×10^{-2} m/s [10,16]; therefore, the trapped particle reaction time in the molten slag surface is sufficiently long, and residual carbon ratio in the coarse slag should be negligible. However, the carbon ratio in the coarse slag is higher than 5% and is varied with the coarse slag sizes [17]. All of these findings suggest that the wall reaction time on the molten slag surface is limited.

In this paper, a more comprehensive model in which the finite reaction time wall reaction model is included, is developed in order to simulate the multiphase reaction and flowing process in a entrained flow gasifier.

2. Mathematical models and simulation method

There are several complicated multiphase physical and chemical processes in an entrained flow gasifier, including gas-particle/droplet flow and reaction (GPFR) process, particle deposition (PD) process, wall reaction (WR) processes and slag flowing and heat transferring SFHT processes, as shown in Fig. 1. Therefore, a comprehensive model used to predict the multiphase flow field and gasifier performance should consider all of these processes.

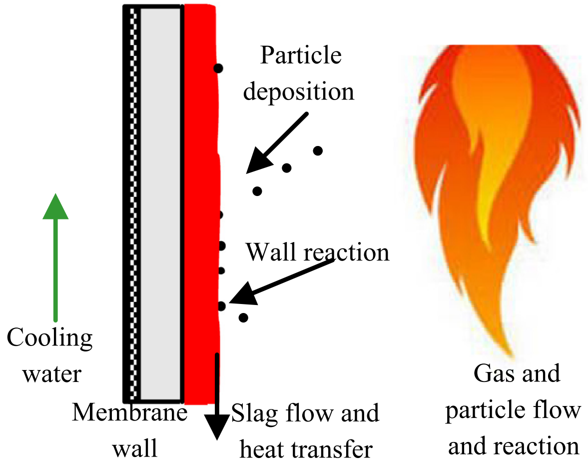

Fig. 1. Schematic representation of multiphase complicated physical and chemical processes in entrained flow gasifier.