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Experimental and numerical study on slag deposition and growth at the slag tap hole region of Shell gasifier

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ABSTRACT

Cold model experimental and dynamic modeling studies on the slag flow and heat transfer at the slag tap hole region of Shell gasifier have been carried out. The cold model experiment was set up to observe the simulated slag deposition. The dynamic model was proposed to clarify the slag accumulation on the wall of slag screen. The results show that the simulated slag can be broken up to slender liquid filaments by the high-speed swirling gas flow, and a part of the filaments can deposit on the slag screen wall. When the surface temperature is below the critical temperature, the slag is totally solidified to solid slag layer. At equilibrium, a liquid slag layer covers the solid slag layer and its surface temperature is higher than the critical temperature. The solid slag layer thickness increases along the slag flow. In addition, the solid slag thickness can be decreased by increasing the operating load and operating temperature.

1. Introduction

Coal gasification is a key technology for clean coal conversion with high efficiency. Entrained-flow gasifier offers several advantages, such as high temperature and pressure, near-zero emission of pollutants, and insensitivity to coal type. Hence, it is a mainstream of development of coal gasification technology [1–4]. There are two typical types of commercial-scale gasifiers which are the coal–water-slurry feed gasifier and the dry coal feed gasifier. The former is used in GE (Texaco) and OMB gasification processes, and the latter is applied in Shell, OMB and GSP etc. technologies [1,5]. In China, the Shell gasifier is mostly employed in chemical industry in the last five years. However, there was often slag blockage at the slag tap hole region during long time operation (Fig. 1), which is an important threat to the safety of Shell gasifier [6]. Thus, study of the slag deposition at the slag tap hole region is necessary for further improvement of its reliability and availability.

Owing to the mass and heat transfer, the physical properties of slag in a membrane wall changed significantly and its flow process is quite complex. Up to now, a number of models have been proposed to describe the flow behavior of the molten slag layer in the entrained-flow gasifier rather than slag tap hole region [7–12]. Seggiani [13] developed a slag building simplified model to simulate time varying slag flow in a Prenflo entrained-flow gasifier, evaluating the temperature and mass flow rate of slag impinging on the wall with a three-dimensional CFD code. Liu et al. [14] and Ni et al. [15] both established a CFD model for slag layer calculation. Kittel et al. [16], Sun et al. [17], and Yang et al. [18] built a model to study the dynamic performance of GSP, Shell, and newly developed Tsinghua oxygen-staged gasifiers, respectively. On the other hand, research on ash deposition was made over the past few decades [19–21]. For instance, Akiyama et al. [22] elucidated the relationship between ash deposition characteristics and ash melting characteristics. The ash deposition tests were conducted using a refractory furnace. Li et al. [23] performed ash deposition experiments at various conversions of a bituminous coal under gasification conditions using a laminar entrained-flow reactor and a deposition probe. However, these studies focused on the details about ash particle deposition, and the results discussed by the analysis tools, such as computer-controlled scanning electron microscope (SEM). All that can help to explain the mechanism of the particle deposition, but it is difficult to know the gas–liquid two-phase flow behavior at the slag tap hole region.

The objective of this work is to perform the cold model experiment and modeling study to explain the reason of slag blockage at the slag tap hole region of Shell gasifier. Furthermore, the effects of deposition rate and operating temperature on the thickness of solid slag layer are also analyzed. Finally, the method to eliminate slag block is also proposed.

2. Experimental system

The liquid slag was simulated using syrup and their physical properties were shown in Table 1. It can be seen that the viscosities of syrup and slag show almost equal variable scope, and the syrup density is a little smaller than that of slag.

The schematic diagram of the cold model experimental system is given in Fig. 2. The geometric similarity ratio of the cold model to

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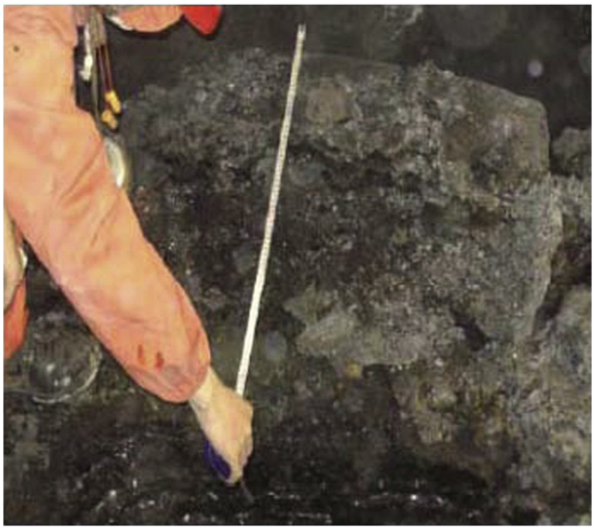

Fig. 1. 2 m circular slag block.

the prototype is about 1:8. We define the region between the slag tap hole and bottom of the slag screen as slag tap hole region. The air streams supplied from fan are measured by rotor flow meters and then discharge from four nozzles which are located at an angle of 4.5° with respect to the nozzle chambers in radial direction. Below the slag tap hole, the gas flow makes circulating movement with the central part rising. The mass flow rate of syrup is controlled by adjusting a valve located at the discharge line of the air cylinder. Flexible PVC tubes capable of withstanding high pressures are used to carry the experimental liquid to the overflow tank. A digital video camera is used to record the gas–liquid interaction process at the slag tap hole region. Under full-load operating condition, the exit air velocity of the nozzle is 70 m/s and the feed rate of syrup is 71.11 kg/h at the slag tap hole.

To study the slag deposition behavior at the slag tap hole region, two parameters were introduced:

$$a = \frac{S_a}{S} \times 100\% \tag{1}$$

$$d = \frac{w_{in}}{w_t} \times 100\% \tag{2}$$

where a is the adhesion rate, S_a is the surface area occupied by deposited syrup, S is the surface area of slag screen, d is the deposition rate, w_{in} is the mass flow rate of syrup supplied to the slag screen wall surface, and w_t is the total mass flow rate of syrup at the slag tap hole. ImageJ is a Java-based image-processing program used for the acquisition and analysis of images. Following the deposit experiment ImageJ was employed here to calculate adhesion rate and widths of the syrup ligaments. The value of w_{in} was estimated by adhesion rate, surface area of slag screen, syrup density and widths of syrup ligaments.

Table 1
Physical properties of liquid slag and syrup.

Liquids	Viscosity (Pa·s)	Density (kg·m^{-3})
Liquid slag	5–25	2535
Syrup	5–30	1330

3. Model description

The following assumptions are introduced here to describe the slag flow at the slag tap hole region. (1) 70% of the ash in coal is led through the slag tap hole located at the bottom of the gasifier and subsequently quenched in a water bath, the other 30% ash is entrained out of gasifier by syngas as fly ash. (2) The heat flux from the gas phase by radiation to slag surface was ignored below the slag tap hole (Fig. 3). (3) The phase transition temperature between the liquid and solid slag layers is the critical temperature. (4) The temperature field of slag is a linear distribution. (5) The density, specific heat and thermal conductivity of the slag are constants. The slag flow model was built based on Seggiani's method [13] and presented as follows.

When the surface temperature is lower than the critical temperature T_{cv}, the mass and energy conservation equations were written for each control volume of ith cell (Fig. 4) as follows.

Mass conservation equation is

$$\rho \frac{d\delta_i}{dt} = \frac{m_{in,i}}{A_i} \tag{3}$$

where δ_i is the slag deposit thickness, t is time, ρ is the slag density, $m_{in,i}$ is the mass flow rate of slag deposition, and A_i is the slag screen wall surface.

Energy conservation equation is

$$\rho c \frac{d(T_i\delta_i)}{dt} = -q_{out,i} + \frac{m_{in,i} c T_{in,i}}{A_i} \tag{4}$$

where T_i is the average slag deposit temperature, c is the heat capacity, $T_{in,i}$ is the temperature of slag deposition and we assume its value is equal to operating temperature, $q_{out,i}$ is the heat flux from the slag to the membrane wall and can be written

$$q_{out,i} = \frac{2\lambda_m \lambda_s}{\lambda_m \delta_i + \lambda_s \delta_m}(T_i - T_m) \tag{5}$$

where T_m is the average temperature of the water-cooled membrane wall, λ_m and λ_s are the thermal conductivity of the water-cooled membrane wall and slag, respectively. δ_m is the thickness of the water-cooled membrane wall.

When the surface temperature is higher than the critical temperature, a liquid slag layer begins to appear, at this time, the mass, energy, and momentum conservation equations can be expressed using the following equations.

Mass conservation equation is

$$\rho \frac{d\delta_i}{dt} = \frac{m_{in,i} + m_{ex,i-1} - m_{ex,i}}{A_i} \tag{6}$$

where $m_{ex,i}$ is the discharging slag mass flow rate.

Energy conservation equation is

$$\rho c \frac{d(T_i\delta_i)}{dt} - \rho \frac{d\left(\delta_{s,i}\right)}{dt} q_f = -q_{out,i} + \frac{m_{in,i} c T_{in,i} + q_{ex,i-1} - q_{ex,i}}{A_i} \tag{7}$$

where $\delta_{s,i}$ is the solid slag thickness, q_f is the slag fusion heat, and $q_{ex,i}$ is heat flux in the slag flowing out of the control volume.

Momentum conservation equation is

$$\frac{d}{dx}\left(\eta \frac{dv}{dx}\right) = -\rho g \cos\beta \tag{8}$$

Where η is the viscosity, v is the slag velocity at the distance x, g is the gravity, and β is the slope of the wall.