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Vision-based investigation on the ash/slag particle deposition characteristics in an impinging entrained-flow gasifier

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HIGHLIGHTS

- A hot model gasifier combined with advanced visualization technique is applied.
- Ash/slag particle characteristic and its deposition layer behavior are studied.
- An ash/slag deposition layer is formed under low operating temperature of gasifier.
- The detachment of ash/slag layer is classified into three typical patterns.
- Detach after warping and fracturing is the commonest in low temperature slagging.

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ABSTRACT

Coal gasification is widely used for chemical production as well as energy generation, and slag tapping process is crucial to entrained-flow coal gasification, before which particle deposition play an important role in slag formation. In order to investigate the slag tapping under special or abnormal operating conditions, the ash/slag particle deposition and ash/slag layer behavior characteristics have been studied based on a bench-scale impinging entrained-flow gasifier. High temperature endoscopy combined with high speed photography is applied to obtain images inside the gasifier and image processing techniques are used to distinguish the object from the high brightness background. The results show that an ash/slag deposition layer is formed under low operating temperature. In the case of particle deposition: High temperature particle (HTP) with medium size would slide on ash/slag layer after impacting, low temperature ash/slag on the deposition layer adheres on the particles and detach from the deposition layer together. HTPs with big size would attract low temperature ashes while travelling in gasifier space and ash/slag surface after impact, then form a low temperature particle (LTP) group with high temperature core and detach from the basic ash/slag layer. LTPs with big size and high space speed would impact and embed into the ash/slag deposition layer, then particle temperature rises while particle volume decreases. The embedded particles hardly detach from the basic layer. The low temperature ash/slag deposition layer would detach from the old slag layer on refractory wall, and the detachment of ash/slag layer is mainly classified into three typical patterns according to the behaviors of the detach process: detach after sliding pattern, detach after tilting and shaking pattern, detach after warping and fracturing pattern. Detachment after warping and fracturing is the commonest pattern of ash/slag deposits behavior that has been observed. Due to the huge volume of detached pieces, it could be the major source of slagging under abnormal operating condition. Under certain extreme conditions, slag tap hole would be blocked by the bridging of huge ash/slag deposits pieces and leads to overpressure of gasification chamber and slagging failure. In industrial applications, the results of this study would be the theoretical support for the suggested minimum load and suggested feeding period of the gasifier during the unique online pressurized continuous coal-water slurry feeding technique of the opposed multi-burner (OMB) gasification.

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1. Introduction

As one of the most cleanest and efficient technologies to covert coal into hydrogen, electricity, and chemical products, coal gasification plays an important role in human history and the entrained-flow gasification technology has been paid more attention recently. China initiated the economic reform in the late 1970s [1] and Texaco (GE) coal-water slurry (CWS) gasification technology was firstly introduced in China during the 1990s, which came after a variety of gasification technology has been applied [2,3]. After several decades of development, the opposed multi-burner (OMB) impinging entrained-flow coal water slurry (CWS) gasification technology [4], which was developed by East China University of Science and Technology (ECUST) has become one of the leading technologies in the world gasification market [5]. More than 100 gasifiers have been built or under construction, which has made great contributions to the development of clean coal technology in China.

The OMB entrained-flow gasifier is operated at high temperature and high pressure. The operating temperature is usually 50 K higher than the coal ash fusion temperature (FT) for the purpose of liquid slag tapping [6]. Under such a high temperature, most of ash/slag particles generated from CWS gasification are molten and frequently impact the refractory wall. Some of those particles adhere to the surface of refractory wall and the others rebound back to the space of gasifier after impact [7]. The deposition characteristics of ash/slag particles in the gasifier are always the research hotspot in the study of gasification process, and it is highly related to the operating conditions. At present, it is difficult to observe the dynamic deposition behavior of ash/slag particles directly in a gasifier due to the complicated environment under hot operation. Thus, the investigation of particle deposition characteristics in a hot model gasifier with advanced visualization technologies is very important.

The research of particle deposition is mainly conducted by experimental test and model prediction. Many researchers have carried out a number of studies on the ash deposition characteristics in combustion facilities. Wang et al. [8] divided the ash deposition process into eight sub-models, and the local deposition properties of coal ash were studied by SEM, X-ray and image analysis techniques [9]. Lee et al. [10] studied the coal slagging propensity in a pulverized coal-fired furnace based on CCSEM fly ash data and CFD technique. The predicted slagging potential and deposition patterns of three coals are consistent with the observations. Walsh et al. [11] proposed a model that combines ash melting temperatures with slag viscosity to predict the probabilities of particles sticking on the wall in the consideration of particle impinging and sticking process. Based on the viscosity model proposed by Walsh, Richards et al. [12] developed a model to simulate deposition behavior of ash under slagging conditions. This model was coupled with a comprehensive combustion code to investigate the effects of ash deposition rate, thermal conditions, and deposit chemistry on the deposits growth in a pilot-scale combustor. Fan et al. [13] proposed a model to predict the flow field, the temperature field and the deposits growth behavior under slagging conditions. Borello et al. [14] modelled the ash deposition within a biomass furnace, they computed the ash deposit thickness and found the deposition rate comparable with that experimentally measured in previous analysis [15]. Shao et al. [16] analyzed and simulated the ash deposition behavior for co-firing peat with lignite by mathematical models where interactions between fuel chlorine, alkali and ash particles are parameterized. The dependences of ash deposition rate and ash chlorine content on the fraction of peat are modeled. Tong et al. [17] proposed a numerical model for fouling on tubes of waste heat recovery equipment. The particle deposition was determined by the energy balance model and the effects of inlet velocities and different particle diameter on the fouling rates are simulated. Based on a one-dimensional down-fired combustor, Li et al. [18,19] studied the ash deposition characteristics during pulverized coal combustion process, and compared the deposition behavior of fly ash under oxy-fuel and conventional combustion conditions.

Experimental and simulation studies on the ash deposition characteristics in the gasifier are also conducted by many researchers. Seggiani [20] established an integrated model including particle deposition and slag flow to evaluate the effects of operating condition changes on the slag behavior. Shimizu and Tominaga [21] studied the char particle deposition behavior on the molten slag surface under high temperature gasification conditions and proposed a simple model to evaluate the probability of char capture by molten slag surface. Ichikawa et al. [22] conducted deposition experiments to examine the mechanism of char adhesion on the heat exchanger tube in a bench-scale coal gasifier. Barroso et al. [23] used an entrained-flow reactor to characterize the effects of coal types, blend composition and operation conditions on the slag deposition behavior. By analyzing the morphology, structure, composition and sintering strength of the deposits adhering to the wall of a two-stage entrained-bed coal gasifier, Shuntaro et al. [24] classified the deposits into three types: powder, lump, and fused slag. Li et al. [25] found the particle capture efficiency is a function of coal conversion by studying ash deposition behavior at various conversions of a bituminous coal under gasification conditions. Ni et al. [7] developed a sub-model for predicting slag deposition by defining the excess rebound energy required to establish the rebound criterion. Liang et al. [26] studied the slag deposition and heat transfer behavior of membrane wall in a pilot-scale entrained flow gasifier, an calculation method based on the heat transfer rule is developed to predict the average slag layer thickness and inner temperature of membrane wall.

Different research methods have been applied in the study of particle deposition and deposition layer behavior, and the features of these methods can be simply concluded as shown in Table 1. The major difficulty of experimental methods is the reproduction of the environment of the particle and the deposition layer, including the flow-field, heat and mass transfer, temperature, randomicity (particle deposition), as well as the surface characteristic of deposition layer. Numerical simulations could be a reasonable way to overcome this limitation, which requires skilled UDF coding, and the validation work need supports from the basic experimental results. Due to the complex environment inside the entrained-flow gasifier, direct experimental method could be a complementary approaching for this study. However, this method also encounters some limitations such as sampling (severe condition for particle and deposition layer online sampling), observing (high temperature and massive particle disturbing for endoscope), as well as pressure reproducing (safety issues). Since the sensitivity and imaging resolution of the camera, the temperature tolerance and stain resistance of the endoscopy have greatly improved, visualization is becoming an intuitive and appropriate approach to study particle deposition characteristics in a real gasifier. Based on the advanced visualization techniques, Gong et al. [27] studied the particle deposition characteristics in an OMB gasifier. The particle deposition process is visually displayed and the probabilities of the occurrence of four particle deposition types are statistically analyzed.

Table 1
Features of different research methods in particle and deposition layer study.

Research method	Features
Numerical simulations/ Modeling research	Complex conditions and environment can be simulated Results need validation due to simplifications
Cold model experiment	Simple system, less variables and accurate flow field Hard to reproduce the influence of heat
Sampling experiment/Drop tube furnaces	Efficient on single particle tracking and sampling Difficult in deposition layer behavior representing