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Original Research Paper

An experimental study of ash particles adhesion force in flue gas

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ABSTRACT

In this study, experiments and analyses have been carried out to investigate the influences of denitrification and flue gas Waste Heat Recovery Systems (WHRS) on ash particles adhesion force. With use of a denitrification system, it is found that the ash particles adhesion force is strongly influenced by the mass ratio, *R*, of $(NH_4)HSO_4$ to ash. Three influencing zones are identified, i.e., little effect zone ($R < 1:150$), intermediate effect zone ($1:150 < R < 1:60$), and huge effect zone ($R > 1:60$). It is necessary to operate in the little effect zone in order to avoid ash deposition in the air preheater. With use of a WHRS, it is found that the ash adhesion force is strongly affected by the flue gas temperature in comparison with the Engineering Acid Dew Temperature (EADT). With decreasing temperature below the EADT, both the collected ash amount and ash adhesion force rise, and the detected particles size increases, indicating particle accumulation that improves ash collection efficiency.

1. Introduction

Denitrification and flue gas Waste Heat Recovery Systems (WHRS) have been widely adopted in power plant boilers in China in recent years for energy conservation and mitigation of environmental pollutants [1]. Flue gas cleaning [2] is important for mitigating CO_2 and NO_X in thermal power plants. Selected Catalytic Reduction (SCR) and Selected Non-Catalytic Reduction (SNCR) are proven denitrification technologies worldwide. Operating practice shows that NH_3 may slip from SCR or SNCR and react with SO_3 in flue gas to produce ammonium hydrogen sulfate – $(NH_4)HSO_4$ – which is sticky and may cause severe ash deposition in the air preheaters [2,3]. Generally, a WHRS is mounted at the entrance of a dust collector. The temperature of flue gas drops passing through WHRS, sometimes to below the acid dew point (ADT). Practical operating data indicated that ash collection efficiency was improved with use of a WHRS [3]. Actually, both ash deposition in air preheater and improvement of ash collection efficiency are closely related to ash particles adhesion force. Thus, studies on ash particles adhesion force have aroused great interests in recent years.

The general powder studies by Salazar-Banda et al. [4] and Ermis et al. [5] revealed significant changes in adhesion due to particle shapes and physical properties. Rutland et al. [6] measured the adhesion force between two cellulose spheres. Kumar et al. [7] measured the adhesion force between silica particles and rough surfaces. Parsons et al. [8] incorporated surface roughness into the calculation of surface forces. Petean and Aguiar [9] found that the true area of contact is also an important factor influencing the adhesion between particles. Price et al. [10] investigated the effect of humidity on adhesion properties of pharmaceutical powder. Qing et al. [11] studied the influence of humidity on surface adhesion force of Si wafer.

In terms of studies on ash particles, Kanaoka et al. [12] evaluated the adhesive force and shear stress of coal fly ash particles from pulverized coal combustion at high temperature. Wang [13] conducted experiments measuring ash particle adhesion force. Lin et al. [14] carried out systematic agglomeration experiments in a straw-fired laboratory-scale fluidized bed combustor, and proposed a theoretical correlation of ash adhesion force. Naganuma et al. [15] found that the wettability of the thermally sprayed materials with respect to the condensed liquid phase ash contributes to the adhesive behavior. Borello et al. [16] predicted ash deposition of a non-conventional biomass furnace. Tong et al. [17] developed a numerical method to simulate the fouling processes on tubes.

Nevertheless, studies on ash particles adhesion in real-process flue gas are scarce. To authors' knowledge, investigation of the influences of $(NH_4)HSO_4$ content and flue gas temperature at the relatively low temperature regime on ash particles adhesion has never been conducted. To this end, this study focuses on experi-

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mental investigation of the influence of $(NH_4)HSO_4$ content due to the adoption of SCR or SNCR denitrification technologies and the effects of flue gas temperature, humidity, and sulfuric content due to the use of WHRS on ash particles adhesion force. As required by the Chinese National Standard, the abruption method [18] was employed here to measure the adhesion force. The ash sample was collected from an ash bucket of an electric precipitator without $(NH_4)HSO_4$ initially, and mixed with given amount $(NH_4)HSO_4$ to prepare samples with various mass ratios of $(NH_4)HSO_4$ to ash. The ash particles diameter distribution is similar to that in a practical air-preheater. The artificial flue gas was prepared via spraying given amount of ash particles and dilute sulfuric acid into an airflow of preset temperature and humidity. The relations between particle adhesion and accumulation and gas temperature were emphasized. Overall, this study aims at improving dust collection efficiency for real process via enhancement of ash accumulation.

2. Description of experiment

2.1. Experimental system

Several methods have been used for measuring adhesion force, such as the centrifugal method [4], the atomic force microscope [7], the electric field detachment method [19], the aerodynamic detachment [19], and the vibration method [19]. In China, however, the abruption method [18] is the National Standard for measuring adhesion force. Thus, the abruption method is adopted in this study and described in detail below.

Fig. 1 shows the experimental system, including (a) the schematic diagram, (b) the force analysis, and (c) a photo of the real setup. The apparatus is reformed from a TG628A analytical balance. The trays of the balance made of stainless steel are very heavy; and thus, were removed in the present experiment. The measuring range of the balance is 200 g with a sensitive quality of 1 mg. The two sections in the testing system, i.e., the sample section and the balance weight section, are mounted at the opposite side of the balance.

The sample section is consisted of an upper barrel, a lower barrel, a fixture and an adjustable support. Its details are shown in Fig. 2 without the adjustable support. The barrels are made of 304 stainless steel. The lower barrel is of a cup shape, whose end is sealed by a stainless steel plate of 1.5 mm thick. The fixture is composed of a sleeve and a stainless steel hoop. The inner diameter of the sleeve is the same as the outer diameter of the barrel. By laser cutting the sleeve vertically, it was divided into two smooth arc work pieces. The two barrels and the fixture are assembled together to form a big cup with outside steel hoop to prevent disassembling. The collected ash is put into the assembled cup and pressed by different weights on top of the ash. The diameter of the weights is the same as the inner diameter of the barrels, which guarantees a uniform pressing to the ash. The adhesion force is closely related to the weights. There is a light rope on top of the upper barrel. The assembly together with the pressed ash is hanged at one side of the balance.

There is a lifting platform just beneath the hanged assembly to support it. The dimension of the platform is 100 mm long, 100 mm wide, and maximum 180 mm high. The platform height is adjustable by its rotary knob to ensure a proper location of the assembly. Since the adhesion force is so small that a tiny motion or external force may lead to measuring error. To reduce such errors, the lifting platform was pasted on the balance floor with glue to eliminate the effect of motion, and the seal steel plate and the barrels were precisely cut by a laser to minimize the contact force.

The weight section is comprised of a water container, a micro-injector, and a plastic plate. The water container is put on the plastic plate. The function of the micro-injector is to inject water into the container gently to minimize fluctuation during injection. The overall weight of the water, container, plastic plate are exerted on the rope of the opposite side of the cross beam.

2.2. Data processing

During experiment, the fixture was removed and the two barrels were jointed only by the ash adhesion force. With increasing water injection, the overall weight of the weight section overcomes the adhesion force to pull the barrels apart. Thus, the adhesion force is calculated by

$$F = \frac{W - G}{S} \qquad (1)$$

where F is the adhesion force, W is the overall weight of the weight section when pull the barrel apart, G is the weight of the upper barrel and ash sample in it, and S is the area of the measuring cross-section, namely the abruption area. Force analysis in the sample section is shown in Fig. 1b. The upper barrel is enclosed in the red square.

The adhesion force is greatly influenced by several objective factors, including ambient humidity, different weights and particle diameter. During the experiment, the ash sample was inevitably exposed to air. Mass exchange occurred between air and ash, i.e., water in the ash vaporized from ash or water vapor condensed onto the ash. Thus, the relative humidity has a great influence on the adhesion force. In order to ensure the accuracy of the test, the experimental ambient relative humidity should maintain constant. The exposure time of the ash to air was controlled within about 30 s during each test. In general, use of heavier weights increases adhesion force. During the experiment, five weights were adopted to press the ash sample. The converted pressure was 1.57, 3.66, 5.99, 8.06 and 10.51 kPa, respectively.

A thermo-hygrometer was used to monitor the temperature and humidity. Intelligent humidifier was applied to keep the humidity constant. The instruments used in the experiment are listed in Table 1.

2.3. Experimental procedure

Preparation Before Experiment: Keep the ambient temperature and humidity stable and calibrate the electronic balance in advance.

Assembly of the Weight Section: Assemble the upper barrel and lower barrel together by the fixture and steel hoop. Keep the interface between the barrels clean and in tight contact. Put 25 g ash (measured by a BSM120.4 electronic balance with measuring accuracy of 0.1 mg) into the assembly. Press the ash with a weight for 3 min. Keep the platform and the seal plate clean and put the assembly on the platform slightly. Disassemble the fixture and the steel hoop carefully to prevent the interface from contaminating and misalignment. Otherwise, clean the interface and repeat the above steps. Adjusting the height of the platform carefully until the rope tightens.

Abruption Experiment: Inject water into the water container by the micro-injector slowly. Be sure no vibration caused by injecting water occurs. Watch the balance pointer carefully and stop injecting water until it deviates to the weight section. The assembly without the fixture will be pulled apart because of the weight of the lower barrel and ash. Observe the fracture section of the ash. If it forms a convex or concave surface, the measuring error will increase because the actual fracture section area is larger than the flat area used for computing adhesion force. A photo of the qualified fracture section is shown in Fig. 3.

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