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Experimental and theoretical analyses on the effect of physical properties and humidity of fly ash impacting on a flat surface

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A B S T R A C T

This study investigated the particle-wall collision characteristics of different fly ash particles against a flat surface under dry and humid conditions by experimental and theoretical analyses. The experiment could be applied to simulate the particle deposition in many engineering fields, such as electrostatic precipitators (ESPs), filtration, and agglomerates. The coal used are bituminous coal from Fushun, Liaoning Province (LN) and meager coal from Zhundong, Xinjiang Province (XJ), which are turned into fly ash particles with a diameter of approximately 7 μm using a muffle furnace. The experimental system is designed for an aerosol inlet particle velocity range of 1–7 m/s. A dynamic model is developed to calculate the damping coefficient, contact time, critical impact velocity, and contact displacement under both dry and humid conditions during impact. The results show that the normal restitution coeffcients decrease with increasing density, Young's modulus, and humid condition. Second, based on the dynamic model calculation, the damping coefficient and contact time are obtained with different impact velocities in a collision. The values of the damping coefficient and contact time are larger under humid conditions due to the effect of capillary force. Third, the critical impact velocity increases under humid condition. Finally, the maximum contact displacement versus the impact velocity and the change of total force and velocity versus the contact displacement during a collision are examined.

1. Introduction

Particle deposition in conventional electrostatic precipitators (ESPs) is widely applied in engineering fields, particularly in power plants. Particles are mainly driven by electric field force, drag force, gravitational force, and the buoyancy force (Lei, Wang, & Wu, 2008). Currently, ESPs in coal-fired power plants have many advantages such as long life, easy maintenance, low operating costs, and high collection efficiency of large-size particles; however, the collection efficiency of small sizes are much lower (Sheng & Yao, 2010). Mcdonald, Smith, Iii, and Sparks (1977), Chen and Lai (2004), and Kherbouche, Benmimoun, Tilmatine, Zouaghi, and Zouzou (2016) obtained the particle collection efficiency and the influence of particle deposition in ESPs by experimental and numerical methods. The collection efficiency in ESPs does not take into account the collision characteristics in the boundary layer, but only the particle deposition when the particle reaches the dust-collecting plate. In this study, the collision characteristics of fly ash particles impacting on a planar surface in the boundary layer are investigated by experimental and theoretical analyses.

There have been numerous experimental and numerical studies on micro-scale particles collision under dry condition. Wall, John,

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Wang, and Goren (1990) measured the incoming and rebounding particle velocities using laser Doppler velocimetry and calculated the energy loss during impact with the grain size of 0.516, 2.58, 3.44, 4.90, and 6.89 μm. Li, Dunn, and Brach (1999) conducted experimental and numerical studies to measure the size range of 1–125 μm polydisperse microsphere normal impact data. Kim and Dunn (2007, 2008) developed a model and computational fluid dynamics software to compare the normal coefficient of restitution and the surface-capture velocity with an experiment on low-speed impact. The distributions of particles are 10, 20, 30 and 100 μm. Dong, Han, Li, and Pu (2013) investigated the rebound behaviour of fly ash particles (88 μm, 96 μm, 104 μm) on normal impact into a planar surface using experimental and theoretical analyses. The influences of the particle size and incident velocity of the particle on the damping coefficient, contact time, and critical impact velocity were analysed by comparing the Hertz, DMT (Derjaguin–Muller–Toporov), BD (Brach and Dunn), and JKR (Johnson–Kendall–Roberts) models. Li, Xie, Dong, and Bai (2015) studied the temperature effect of micro-sized SiO_2 particles with diameters ranging from 2 μm to 35 μm impacting on a flat surface through experimental and numerical methods. The effects of particle size, incident velocity, temperature, and damping coefficient on the particle–surface collision were analysed.

Real flue gases entering an ESP have certain humidity. Thus, a thin liquid layer can be condensed in between the particle and the flat surface. The forming of liquid bridge force produced by the liquid layer is given in favour of particle deposition. Many researchers focused on experimental investigations of millimetre-sized particles against flat surfaces with a liquid layer. Ma, Liu, and Chen (2013, 2016) set up a collision experimental system and demonstrated that the rebound behaviours differ with different liquid layer thickness and viscosity. Then, a modified Stokes number was proposed as follows:

$$St_m = \frac{mV_i}{\mu dh} \tag{1}$$

where m is the particle mass, V_i is the impact velocity, μ is the dynamic viscosity of liquid layer, d is the particle diameter, and h is the liquid layer thickness. Gollwitzer, Rehberg, Kruelle, and Huang (2012), Crüger, Heinrich, Antonyuk, Deen, and Kuipers (2016), Antonyuk, Heinrich, Deen, and Kuipers (2009), Kan, Nakamura, and Watano (2015), and Glasstetter, Ricketts, and Wilhelm (1991) calculated the factors affecting energy loss during collision, the capillary force changes with the separating distances and the restitution coefficient versus the liquid layer thickness, viscosity, and Stokes number through experimental methods respectively. Pitois, Moucheront, and Chateau (2000), Butt and Kappl (2009), and Mu and Su (2007) calculated the liquid bridge force, liquid bridge geometry, and the surface roughness effect on capillary force under humid condition respectively. Definitions for static liquid bridge force and dynamic liquid bridge were provided. Static liquid bridge force was defined as the sum of the surface tension force and capillary pressure force, while dynamic liquid bridge was defined as the sum of the static liquid bridge force and viscous force. Under humid condition, the effect of adhesion is increased by capillary force, which makes particle deposition much easier. Zarate, Harrison, Litster, and Beaudoin (2013) calculated the adhesion forces of hydrophilic versus hydrophobic particles in different humid conditions. Givehchi and Tan (2015) presented a new model for airborne nanoparticle filtration by considering the effects of capillary force and plastic behaviour impaction. They concluded that the capillary force between the particle and filters surface increased with humidity. Pakarinen et al. (2005) calculated the meniscus profile using the Kelvin equation and the values for different particle shapes, separation distance, and contact angles. Xu, Lio, Jun, And, and Salmeron (1997), Sedin and Rowlen (2000), And and Qian (2012), and Zitzler, Herminghaus, and Mugele (2002) measured the adhesion force between a nanoparticle and flat surface with an atomic force microscope under different humid conditions. Dörmann and Schmid (2014) investigated the effect of particle diameter and relative humidity on capillary force. They calculated the capillary force for particle–particle and particle–wall collisions.

Despite the above experimental and theoretical studies of impact problems on particle collision, little attention has been paid on micrometre-scale particle collision under humid conditions. This study uses experimental and dynamic methods to analyse the particle-wall collision characteristics under the effect of material properties and humid conditions. In Section 2, the experimental setup was developed to investigate the collision characteristics and analyse the material properties of fly ash particles. In Section 3, the dynamic model was introduced to research normal impact of fly ash particles with a planar surface under dry and humid conditions. In Section 4, the experimental results of the variation of the normal restitution coefficient were discussed with the material properties. Second, the calculation of the damping coefficient and contact time, followed by the calculation of the critical impact velocity value were presented using the dynamic model and then, the results with experimental values were compared. Third, the critical impact velocity is larger under humid condition. Finally, the contact displacement versus contact time as well as the total force and velocity variations versus contact displacement during a collision were calculated.

2. Experimental analysis

2.1. Experimental system

The experimental facility was developed to investigate the collision of fly ash particles on a flat surface under dry and humid conditions. This system, which is illustrated in Fig. 1, is used for measuring the normal incident velocity.

The experimental system is composed of four parts: inlet system, humidity control system, collision unit, and high-speed camera system. Nitrogen supply was divided into two parts to provide the required humidity condition, and then the two air streams were sufficiently mixed to carry the fly ash particles into the test section at an incident velocity of 1–7 m/s. In particular, the gas only ran through the upper tube under dry condition.

The humidity control system consists of two mass flow meters and one BGI collision device (atomizer aerosol generator, BGI Inc., USA). The system can provide the required humid condition, and therefore, the humidity and velocity could be changed by adjusting