Particuology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Particuology

journal homepage: www.elsevier.com/locate/partic

Removal of inhalable particles from coal and refuse combustion by agglomeration with solid nuclei

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ARTICLE INFO

Article history:
Received 25 June 2016
Received in revised form 14 June 2017
Accepted 23 June 2017
Available online xxx

Keywords:
Inhalable particle
Agglomeration
Solid nuclei
Fly ash
Air pollution
Relative humidity

ABSTRACT

Airborne inhalable particles are a potent environmental pollutant. Formed via industrial processes, separation of these particles is difficult using conventional clean up techniques. In this work, solid nuclei particles of different chemical compositions were introduced into an agglomeration chamber with simulated flue gases to investigate their ability to remove these particles. Organic nuclei were able to capture more inhalable particles from coal-derived fly ash than inorganic nuclei, though these proved more effective for the agglomeration of inhalable particles in refuse-derived fly ash. Increasing the diameter of the solid nuclei benefitted the agglomeration process for both types of ash. Varying the local humidity changed adhesion between the particles and encouraged them to aggregate. Increasing the relative humidity consistently increased particle agglomeration for the refuse-derived ash. For coal-derived fly ash, the removal efficiency increased initially with relative humidity but then further increases in humidity had no impact on the relatively high efficiencies. After agglomeration in an atmosphere of 62% relative humidity, the mean mass diameter of inhalable particles in the coal-derived fly ash increased from 3.3 to 9.2 μm. For refuse-derived fly ash, agglomeration caused the percentage of particles that were less than 2 μm to decrease from 40% to 15%. After treatment at a relative humidity of 61%, the mean size of inhalable particles exceeded 10 μm.

Introduction

Recently, particles emitted from industrial processes have been subject to extensive investigation because they are recognized as a serious public health concern. Epidemiologic studies have linked exposure to particulate air pollution to increases in daily morbidity and the deposition of particles in the lungs (Park & Wexler, 2008). Emitted particles, such as those released from coal-fired power plants, contribute significantly to ambient aerosol loading in the atmosphere (Jin, He, Liu, & Hong, 2002). In China, particulate matter now exceeds SO_2 and NO_x as the principal urban pollutant in most major cities (Yao, Li, Xu, Zhuo, & Song, 2009). Although industrial dust-separation processes, such as electrostatic precipitators (ESPs), cyclones, and wet scrubbers, are widely used to remove these particles, their capture efficiency for inhalable particles (particles with diameter of less than 10 μm) is poor (Gallego-Juarez et al., 1999). This results in considerable amounts of particulate matter continuing to be released into ambient air.

There are two major techniques to decrease the concentration of these small particles in combustion flue gases. One aims to improve the capture efficiency via combining conventional approaches. Examples of such hybrid systems include a mixture of ESPs, bag filters, electric filters, electrically energized packed-beds, and electrically energized cyclones (Yao et al., 2009). Another approach involves particle agglomeration, a preconditioning technique that uses external forces to intensify particle collision. This enlarges the average particle size and these larger, agglomerated particles are more easily removed by conventional filtration systems, substantially improving their removal efficiency of inhalable particles. Indeed, agglomeration has been shown to be a simple and economical method to improve the collection efficiency of an ESP system (Chen, Wu, & Mi, 2016).

Particles in a turbulent gas flow can acquire energy from the fluid's motion, increasing a particle's velocity and promoting collision with other particles. Turbulent agglomeration processes are a frequently observed natural phenomena and are widely used in various industries. For example, in atmospheric clouds where large turbulent intensities occur, turbulent agglomeration plays an important role in the early stages of the growth of rain droplets and determining their size distribution (Pinsky & Khain, 1997; Shaw,

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https://doi.org/10.1016/j.partic.2017.06.006
1674-2001/

Nomenclature

A	Hamaker constant, 0.4×10^{-20} J
c_m	Concentration of fly ash (g/m^3)
c_j	Concentration of solid nuclei (g/m^3)
d	Particle diameter (m)
F_{vdw}	van der Waals force (N)
F_c	Capillary force (N)
G	Gravity (N)
K_T	Turbulent agglomeration kernel (m^3/s)
L	Particles distance (m)
R_1	Radius of liquid bridge arc (m)
R_2	Radius of liquid bridge at neck (m)
t	Time (h)
T	Temperature (°C)
u_m	Main gas velocity (m/s)
u_j	Jet gas velocity (m/s)

Greek symbols

α	Half-filling angle for two spherical particles (°)
γ	Surface tension of liquid (N/m)
ε	Turbulent dissipation rate (m^2/s^3)
μ	Gas viscosity (m^2/s)
ρ	Particle density (kg/m^3)

2003). In the food industry, turbulent jet agglomeration has been used for several years to produce agglomerates of powdered foods that have more favorable instant properties (Hogekamp, Stang, & Schubert, 1994; Schuchmann, 1995). And in the chemicals industry, ceramic nanoparticles can be formed by gas-phase synthesis (Hao, Zhao, Xu, & Zheng, 2013). In gas turbines and diesel engines, the unwanted formation of soot in turbulent jet diffusion flames has been studied widely (Kronenburg, Bilger, & Kent, 2000; Wen, Yun, Thomsona, & Lightstone, 2003).

The interaction between particles and a turbulent flow is complex, but numerous computational simulations and theoretical descriptions confirming turbulent agglomeration's practical utility have been reported (Chun, Koch, Rani, Ahluwalia, & Collins, 2004; Derevich, 2007; Liu, You, Yang, & Wang, 2010; Rigopoulos, 2007; Wang, Wexler, & Zhou, 2000). However, experimental studies focusing on the turbulent agglomeration of aerosols remain limited. Duru, Koch, and Cohen (2007) measured the rate of aerosol coalescence in a well-characterized turbulent flow using a phase-Doppler method. The authors found that the values were in good agreement with theoretical predictions that took into account the simultaneous effects of coalescence induced by turbulent shear forces and Brownian motion. Our previous studies (Sun & Guo, 2010; Sun, Zhang, & Fang, 2013) investigated the impact of turbulent jet parameters on the agglomeration of inhalable particles and found that a high gas velocity for a jet and for a vertically injected turbulent gas jet could favor the removal of inhalable particles. Agglomeration experiments with particles exposed to an external field reported by Guo, Yang, and Zhang (2012) suggested that entraining coarse particles to form a gas–solid jet enhanced the agglomeration, and therefore removal efficiency, of inhalable particles (Yang & Guo, 2011). Yan, Chen, and Li (2016) found that the removal efficiency of fine particles emitted by coal combustion increased by 25% when seed droplets of a surfactant were added to the flow, which was then subjected to an acoustic field at a sound pressure level of 130 dB.

The present work aims to build on research into the removal of fine particles from flue gases by investigating the agglomeration, in the presence of solid nuclei, of inhalable particles emitted by the combustion of coal and refuse. Several kinds of large solid nuclei particles (diameter > 100 μm) are introduced into the agglomeration chamber using a gas–solid jet. These solid nuclei included organic polymer materials and inorganic particles.

Table 1
Basic properties of fly ash.

	Coal fly ash	Trash fly ash
Median diameter (μm)	14.36	1.91
Density (kg/m^3)	1838	1304
Moisture content (%)	0.78	2.37
Loss on ignition (%)	3.81	2.19
Content of soluble salt (%)	2.23	49.47

Table 2
Chemical compositional analysis of fly ash.

Element	Coal fly ash (wt%)	Trash fly ash (wt%)
O	48.94	39.97
Al	20.02	1.56
Si	20.01	4.66
C	7.18	7.29
K	0.51	2.85
Ca	0.81	22.81
Fe	1.18	1.69
Cu	1.34	–
Na	–	3.11
Mg	–	0.84
P	–	0.96
S	–	4.65
Cl	–	9.63

Note: – not detected.

Experimental

Materials

The inhalable particle sources were collected from industrial facilities. Coal-derived fly ash particles were collected from an electrostatic precipitator at Qingdao Power Plant while fly ash from refuse combustion was gathered from a bag filter at Qingdao Municipal Incineration Power Plant. The density, moisture content, loss on ignition, and content of soluble salts of the fly ash samples shown in Table 1 were determined according to GB/T16913-2008 and GB 7871-1987. The size distribution of the initial samples was measured by a Rise-2002 laser particle size analyzer (Rise Science Co., Ltd., Qingdao, China).

The samples' chemical compositions were determined using an Energy-350 energy dispersive spectrometer (Oxford Instruments, Abingdon, UK) and are shown in Table 2.

A number of solid nuclei were tested. The organic polymer compounds — modified starch (MS), polyglycol (PG), and polyacrylamide flocculate (PAM) — contained lots of amino or hydroxyl groups, which readily adsorb water from the surrounding environment. The inorganic nuclei — coarse coal fly ash (CCFA), calcium sulfate (CS), and activated carbon (AC) — also had a high affinity for water. Both types were engineered to be strong enough to resist breaking down under the forces exerted by the turbulent gas flow.

Experimental setup

Fig. 1 shows the experimental setup, which comprised a fluidized bed aerosol generator, a gas–solid jet system, measurement apparatus, and a particle agglomeration chamber. The particle agglomeration chamber was a round, transparent pipe with an inner diameter of 116 mm and a length of 600 mm. The two ends of the tube were sealed by plates. The aerosols exited the chamber via a port of inner diameter 20 mm that was fixed in the center of the chamber's base plate. A round, jet nozzle, with an inner diameter of

Please cite this article in press as: Sun, D., et al. Removal of inhalable particles from coal and refuse combustion by agglomeration with solid nuclei. *Particuology* (2017), https://doi.org/10.1016/j.partic.2017.06.006