Journal of Hazardous Materials B121 (2005) 175–181

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

The effect of ash and filter media characteristics on particle filtration efficiency in fluidized bed

Ming-Yen Wey *, Ke-Hao Chen, Kuang-Yu Liu

Department of Environmental Engineering, National Chung-Hisng University, Taichung 402, Taiwan, ROC

Received 24 September 2004; received in revised form 1 February 2005; accepted 17 February 2005
Available online 12 March 2005

Abstract

The phenomenon of filtering particles by a fluidized bed is complex and the parameters that affect the control efficiency of filtration have not yet been clarified. The major objective of the study focuses on the effect of characteristics of ash and filter media on filtration efficiency in a fluidized bed. The performance of the fluidized bed for removal of particles in flue gas at various fluidized operating conditions, and then the mechanisms of collecting particles were studied. The evaluated parameters included (1) various ashes (coal ash and incinerator ash); (2) bed material size; (3) operating gas velocity; and (4) bed temperature.

The results indicate that the removal efficiency of coal ash increases initially with gas velocity, then decreases gradually as velocity exceeds some specific value. Furthermore, the removal of coal ash enhance with silica sand size decreasing. When the fluidized bed is operated at high temperature, diffusion is a more important mechanism than at room temperature especially for small particles. Although the inertial impaction is the main collection mechanism, the "bounce off" effect when the particles collide with the bed material could reduce the removal efficiency significantly. Because of layer inversion in fluidized bed, the removal efficiency of incinerator ash is decreased with increasing of gas velocity.

Keywords: Fluidized bed; Filter; Particle; Coal ash; Incinerator ash

1. Introduction

The use of relatively fine particles as heating or cooling media for coarse materials in gas-solid fluidized beds has been proposed with wide applications in incineration, chemical, food and metallurgical processes. Due to its high heating value, high mass transfer and the ability of continuous operating and capturing harmful material, the fluidized bed reactor has been gradually applied on incineration process. In previous study, fluidized bed could control the pollutants such as acid gases [1], organic compounds [2,3], heavy metals [2] and particulates [3,4] during incineration.

Although the fixed-bed type is the most common device for use in the granular filtration, but the moving bed and fluidized bed have the advantages of continuous operation and regeneration over fixed bed. The collection mechanisms of moving bed resemble that of fixed bed which is developed already [5]. Most recent study on granular bed filtration focused on the applications of moving bed [6–8], not the collection mechanisms. However, the ability and mechanism to remove particulates by a fluidized bed reactor were less studied than the fixed and moving bed. In 1970 and 1980s, the studies of particle filtration by fluidized beds were proceeded because the new type of energy production system such as integrated gasification combined cycle (IGCC) was developed. Knettig and Beeckmans [9], Doganoglu et al. [10] and other workers focused on the efficiency of particle filtration with different parameters mainly on superficial gas velocity, static bed height, different collector particles and distributor. Most of them used the particle generator to produce monodispersed particles (usually about 1 μm). The liquid particles or collector particles coating with a non-volatile liquid were mostly used to prevent re-entrainment of dust in distinguishing between collection and retention of dust. In 1976, Tardos et al. [11] use a numerical solution

* Corresponding author. Tel.: +886 4 22852455; fax: +886 4 22862587.
E-mail address: mywey@dragon.nchu.edu.tw (M.-Y. Wey).

0304-3894/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2005.02.005

of diffusion equation to calculate a single sphere efficiency of small particles for a fluidized bed. Peters et al. [12], Ushiki and Tien [13,14] developed other simulation models to calculate the aerosol removal, the re-entrainment were all neglected to avoid complexity. Ghadiri et al. [15] considered the re-entrainment of the particles from the bed material and noticed that the removal efficiency would decline extensively. However, there are queries to apply these results to the application of fluidized bed on the filtration of combustion gas, especially the chemical compositions of the fly ash are quite different from the dust used in those papers.

Using a fluidized bed filter to filtrate particles, collisions between the particles and bed material occur initially so particles are captured by filter grains. The collection mechanisms include interception, inertial impaction, diffusion, gravitational settling and electrostatic attraction. Each mechanism is mainly related to the characteristics of the particle, collecting media and exhaust gas such as flow velocity and temperature. However, particles captured by the bed material are lost and eluted from fluidized beds in the meantime, so the exit concentration varies. The attrition and elution of particles must be understood as they influence the removal efficiency of particles. The main effects of the attrition and elutriation in fluidized beds are operating flow rate [16–22], bed temperature [18,23], the adhesion of the particles [20,24–27] and the bed material diameter [17,21,22,26]. The parameters have influences on fluidized bed filtration, as the elutriation of particles captured by filter grains increases the exit concentration of particles.

Because of the potential of simultaneous removal of other pollutants in combustion gas, the particle filtration by the fluidized bed reactor deserves to be investigated. The characteristics of ash, filter media and treated gas are important for filtering particles by a fluidized bed. In the present work, the fly ash from a coal fired power plant and a municipal solid waste incinerator were utilized to understand the possibility of using the fluidized bed to remove the fly ash if the fluidized bed is really applied. The evaluated parameters included (1) various ash (coal ash and incinerator ash); (2) bed material diameter (silica sand, 600.5, 770.5, 920.0 μm); (3) gas velocity (U_f) (which correspond to flow rate of 400, 500, 600 L/min at 30° C); and (4) bed temperature (36, 100, 200, 300° C). The particle size distributions and surface/volume diameters (d_{sv}) exiting the fluidized bed filter were also studied.

2. Experimental

2.1. Experimental apparatus

The fluidized bed filter used in this study is illustrated in Fig. 1. The fluidized bed reactor was made of AISI 310 stainless steel. A fluidized bed filter included (1) ash feeder; (2) fluidized bed with a inner diameter of 15.5 cm and a height of 80 cm; (3) electrical heaters by tetrahedral 50 cm × 50 cm and 50 cm high, and the alumina–silica blocks stapled onto an aluminum tetrahedral, insulate the whole facility. The bed temperature was measured by a K-type thermocouple welded on the wall and linked to a proportional integral derivative (PID) controller to regulate the bed temperature. The fluidized bed filter was fitted with a distributor made of stainless plate with mesh #35.

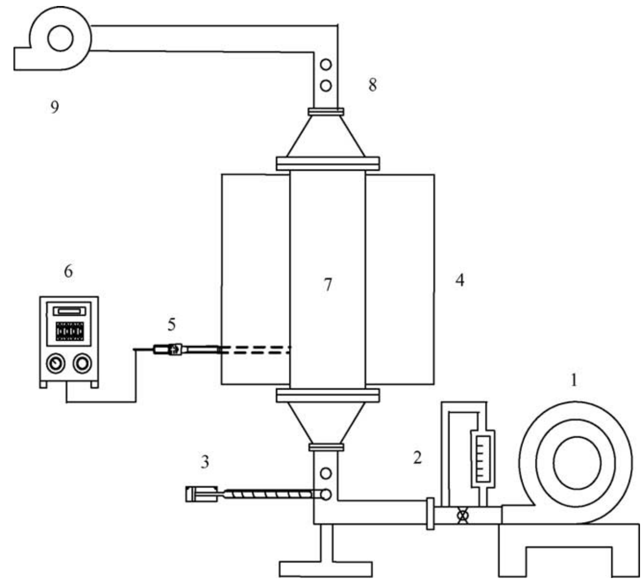

Fig. 1. Fluidized bed reactor: (1) blower; (2) flow meter; (3) fly ash feeder; (4) electrical heater; (5) thermocouples; (6) PID control; (7) fluidized bed filter; (8) sampling location; (9) induced fan.

2.2. Composition of fly ash

The fly ash serving in the study was sampled from a coal fired power plant and an incinerator in Taiwan. The main chemical compositions of the coal ash and incinerator ash are listed in Table 1. There are large variances in the compositions of the different fly ashes. The main compositions of the coal ash are SiO_2, Al_2O_3, CaO and Fe_2O_3, but the main compositions of the incinerator ash are CaO and Cl^-. The particle size distribution of the fly ash was analyzed with a laser-diffraction particle sizer (FRITSCH Analysette 22 COMPACT, analyze range: 0.31–300.74 μm) before experiment. Figs. 2 and 3 show the particle size distribution of the coal ash and incinerator ash.

Table 1
Chemical compositions of the fly ash from a coal fired power plant and municipal solid waste incinerator

Compositions	Coal ash	Incinerator ash
SiO_2 (%)	42.9	7.6
Al_2O_3 (%)	22.2	3.4
CaO (%)	7.5	35.8
Fe_2O_3 (%)	7.7	1.2
MgO (%)	2.2	1.4
K_2O (%)	0.6	–
TiO_2 (%)	1.0	–
Cl^- (%)	–	17.7

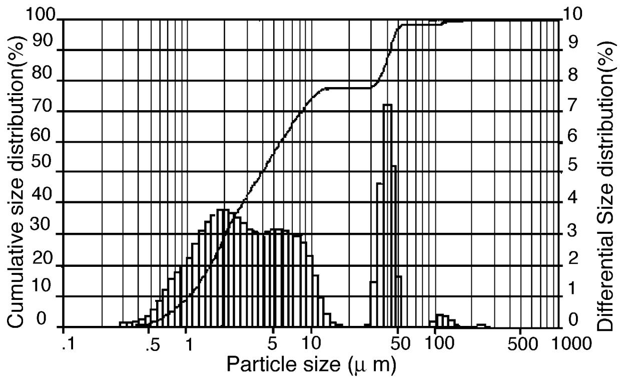

Fig. 2. Particle size distribution of coal ash.

2.3. Experimental procedure

Before the experiment was processed, the inner column of the fluidized bed and all apparatus were clean-up to avoid error during the experiment. Then the bed material was put into the fluidized bed and preheated to the setting temperature of each experiment.

The gas flow rate (at room temperature) was set at 400, 500, and 600 L/min. The air is supplied by a blower and an induced fan then be heated until the set temperature is reached. The attrition and elutriation of bed materials increased the concentration of coal ash. The system keeps operating for 3 h to reach a steady state before the injection of fly ash. The elutriation rate of the bed material is measured and subtracted from the data of the collecting particles. Then, the simulated fly ash was injected into the fluidized bed at the rate of 0.83–0.93 g/min. The isokinetic sampling at outlet of the fluidized bed was also started simultaneously. The polytetrafluoroethelene filter was renewed every 6 min during sampling period and was weighed by an ultramicrobalance.

The fluidized bed was maintained at steady state (i.e. desired temperature and steady operating conditions) for each run and rerun for three times at each condition. Experiments show good reproducibility in this study.

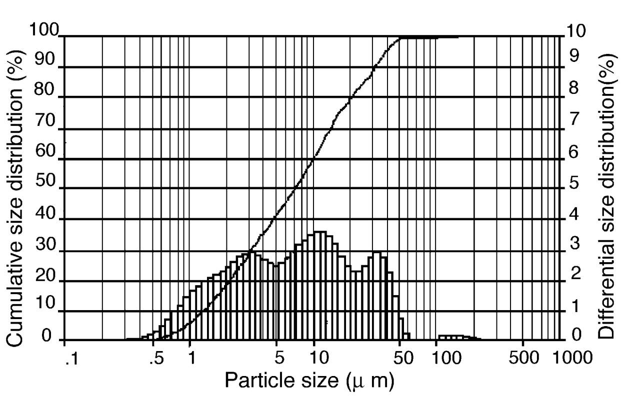

Fig. 3. Particle size distribution of incinerator ash.

2.4. Analysis of simulated fly ash

The flue gas containing fly ash was sampled after flowing through the fluidized bed filter. The filters containing fly ash were weighed and compared with that before sampling. Finally, the fly ash was scraped from the polytetrafluoroethylene filters and analyzed with a laser-diffraction particle sizer to study the variation of particle size distribution passing through the fluidized bed and the removal efficiency of submicron fly ash under various operating conditions.

3. Results and discussion

3.1. Removal efficiency of coal ash under various operating gas velocity

The minimum fluidization velocity (U_{mf}) is determined using the formula derived by Wen and Yu [28] to elucidate the influence of operating velocity on the removal efficiency. Fig. 4 shows the effect of operating gas velocity on removal efficiency of coal ash. The removal efficiency of coal ash increased with the increasing of operating gas velocity between 0.55 (which correspond to $U_f/U_{mf} = 1.4$) and 0.69 m/s ($U_f/U_{mf} = 1.7$), then is decreased as gas velocity increases between 0.69 and 0.83 m/s ($U_f/U_{mf} = 2.0$). The removal efficiency that is increased with a increasing of gas velocity from 0.55 to 0.69 m/s is attributed to the also increasing of Stoke's number (*St*). Increasing *St* number will enhance capture efficiency for inertial impaction of the particles. In addition, the inclined gas velocity improved well mixing of the bed material and fly ash which also increased the capture efficiency of coal ash due to the enhancement of impact. The lower efficiency with the increasing of gas velocity between 0.69 and 0.83 m/s may be the fact that dust particles collided with silica sand at relatively high gas velocity then bounced off on contact. The result is similar to that found by Fayed and

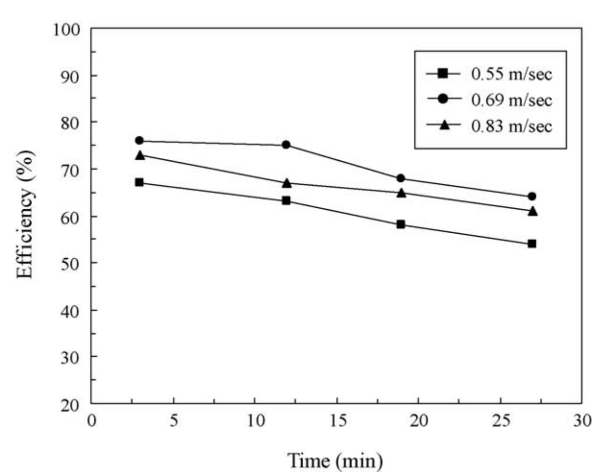

Fig. 4. Effects of operating gas velocity on removal efficiency of coal ash (sand particle size: 770.5 μm, bed temperature: 200 °C, static bed height: 21 cm).

Otten [29]. The efficiency due to diffusion is dependent on the dimensionless Peclet number (*Pe*), where *Pe* is directly proportional to operating velocity. The removal efficiency for diffusion should decrease as *Pe* increase. In addition, the elutriation of fines reduces the removal efficiency of particle filtration with an increasing of gas velocity [21,27].

3.2. Removal efficiency of coal ash under various silica sand diameter

The effect of sand particle diameter on removal efficiency of coal ash is shown in Fig. 5. The removal efficiency of coal ash decreased with increasing of silica sand diameter between 600.5 and 920.0 μm. The results are attributed to the surface area of bed material decreased with an increasing of silica sand diameter. Due to high surface area in fluidized bed, coal ash is captured easily. Moreover, the capture of coal ash by interception and inertial impaction mechanisms is enhanced with high surface area under the same flow rate. This result is similar to Lozano et al. [30] who found that removal efficiency of ash decreased with increasing of bed material diameter.

3.3. Removal efficiency of coal ash under various bed temperatures

Fig. 6 plots the effect of bed temperature on removal efficiency of coal ash. The result revealed that the removal efficiency of coal ash increased with increasing of bed temperature between 36 and 200 °C, then decreased between 200 and 300 °C. The influences of temperature on particle removal are: (1) The operating gas velocity and viscosity increase with the increasing of temperature, so *St* number varies. (2) The removal of smaller particles is enhanced with the diffusion mechanism at high temperature. (3) Elutriation rate increases as the temperature increases [31]. (4) Particles bounce off from the bed material as above mentioned. When bed temperature increased from 36 to 100 °C and 200 °C, the gas velocity increased 1.21 and 1.53 times and the viscosity increased 1.14 and 1.35 times. Therefore, the *St* number increased about 1.06 and 1.13 times respectively. The removal efficiency of coal ash increased with increasing of bed temperature because the inertial impaction was dominant as the *St* number increased. The diffusion also raises the removal efficiency for smaller particles. When the bed temperature increased from 200 to 300 °C, the velocity increased 1.22 times but viscosity increased 1.53 times, so *St* number decreased to 0.8 times and the removal efficiency declined. The bounce off and elutriation of particles also reduced the removal efficiency at high temperature.

3.4. Removal efficiency of coal ash under various operating time

The concentration of the fines in the fluidized bed will increase due to accumulation and affect the capture efficiency. Therefore, the filtration process is rather a dynamic process than a steady one. A longer operating period was performed to see the influence of time. Fig. 7 depicts the removal efficiency of coal ash under various operating time. The capture efficiency declined as operating time increased. When operating time reached 133 min, the efficiency decreased to zero which demonstrated that the accumulation and elutriation of the fines gradually overcame the capture of particles by the bed material. So the regeneration and renewing of the bed material must be considered in the application of the fluidized bed.

3.5. Removal efficiency of incinerator ash under various operating gas velocity

Fig. 8 shows the effects of operating gas velocity on the removal efficiency of incinerator ash. The experimental results revealed that increasing gas velocity resulted in the reduction of the removal efficiency of incinerator ash. Moreover, the partial of the particle removal were through

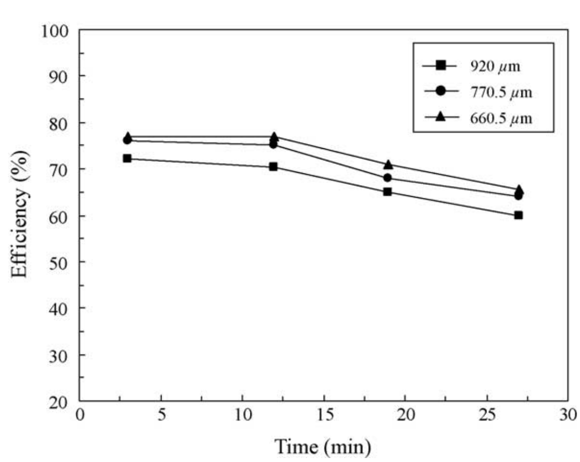

Fig. 5. Effects of sand particle diameter on removal efficiency of coal ash (flow rate: 500 L/min, bed temperature: 200 °C, static bed height: 21 cm).

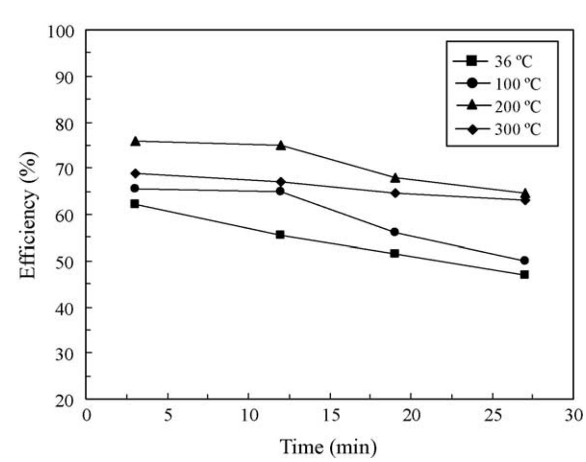

Fig. 6. Effects of bed temperature on removal efficiency of coal ash (flow rate: 500 L/min, sand particle size: 770.5 μm, static bed height: 21 cm).

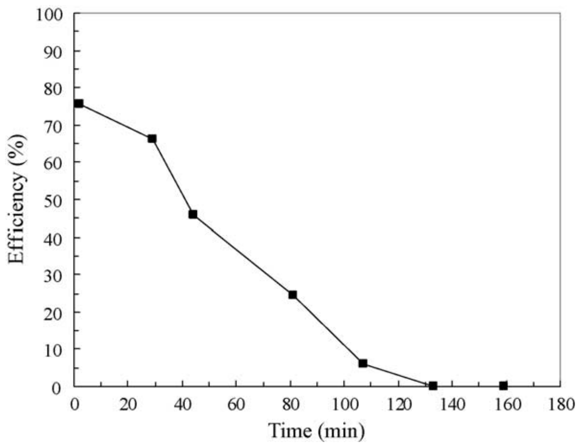

Fig. 7. Removal efficiency of coal ash under various operating time (flow rate: 500 L/min, sand particle size: 600.5 μm, bed temperature: 200 °C, static bed height: 21 cm).

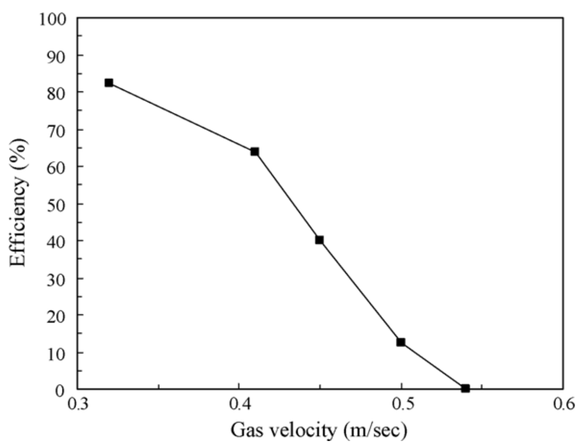

Fig. 8. Effects of gas velocity on removal efficiency of incinerator ash (sand particle size: 770.5 μm, bed temperature: 36 °C, static bed height: 21 cm).

the gas distribute plenum under gas velocity between 0.32 (15%) and 0.41 m/s (11.5%) at cold-modal. However, the removal by gas distribute plenum was not found for operating flow rate between 0.45 and 0.54 m/s. It was interesting that the removal efficiency was noted to be zero under 0.54 m/s.

The influence of the gas velocity on the removal efficiency of coal ash was different than that of the presence of incinerator ash. This is because the density of incinerator ash (3.2 g/cm^3) is heavier than coal ash (2.3 g/cm^3), and that is

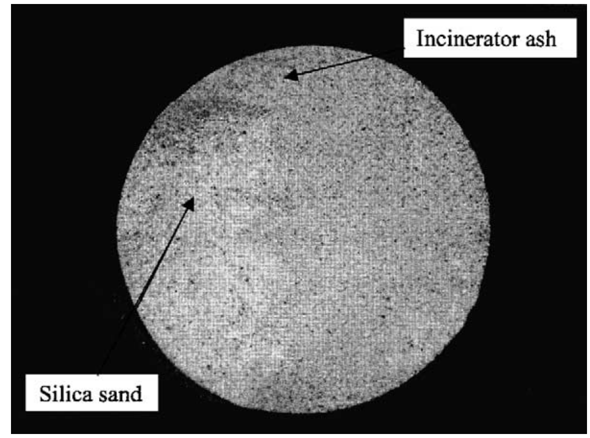

Fig. 9. The layer inversion phenomenon of the incinerator ash (flow rate: 500 L/min, sand particle size: 770.5 μm, bed temperature: 36 °C, static bed height: 21 cm).

heavier than silica sand (2.6 g/cm^3), too. The fluidized bed changed to binary system by incinerator ash feeding and the layer inversion phenomenon [32] occurred if the gas velocity increased. With further increase in gas velocity, the bed may completely segregate opposite of the initial condition. Therefore, the declined removal efficiency of incinerator ash with an increasing of gas velocity from 0.32 to 0.54 m/s was because of layer inversion in fluidized beds. The existing of the incinerator ash on the top surface of the bed shown in Fig. 9 elucidated the layer inversion phenomenon. The difference between the removal of the incinerator and coal ash is mainly attributed to the different compositions of both, so the influence of physical/chemical characteristics of ash on fluidized bed filtration needs to be discussed in advance.

3.6. *Variation of particle size distribution after flowing through fluidized bed*

Because of the outlet particle size distribution of all runs in the present study have similar characteristics (in bimodal distribution), the surface/volume diameters (d_{sv}) of the outlet particles under various operating conditions are chosen to discuss. Table 2 lists the surface/volume mean diameter (d_{svm}) of coal ash at outlet of fluidized bed filter and Table 3 lists the cumulative fraction of coal ash for different particle size. Runs 19 and 20 depict that d_{svm} of particles at outlet

Table 2
Surface/volume mean diameter (d_{svm}) of coal ash at outlet of fluidized bed reactor under various operating conditions

Run	Bed temperature (°C)	Gas velocity (m/s)	Static bed height (cm)	Particle size (μm)	d_{svm} (μm) at 26–30 min[a]
3	36	0.55	21	770.5	3.63
11	100	0.65	21	770.5	8.27
16	200	0.69	21	920	4.37
19	200	0.69	21	770.5	4.49
20	200	0.83	21	770.5	6.39
22	200	0.69	21	600.5	5.00
28	300	1.00	21	770.5	5.13

[a] Initial d_{svm} of coal ash is 2.31 μm.

Table 3
Cumulative fraction of coal ash (by volume) with various particle size at outlet of fluidized bed reactor under various operating conditions

Particle size (μm)	Cumulative volume fraction (%)						
	Run 3	Run 11	Run 16	Run 19	Run 20	Run 22	Run 28
<1.0	5.55	2.18	4.47	4.24	3.13	3.93	3.96
<10.0	42.96	17.55	36.71	39.00	24.00	30.78	30.22
<50.0	90.53	66.75	86.13	74.75	54.99	97.74	91.16
<100.0	100.00	100.00	98.35	100.00	94.30	100.00	100.00
<200.0	100.00	100.00	99.34	100.00	99.16	100.00	100.00

Table 4
Surface/volume mean diameter (d_{svm}) of incinerator ash at outlet of fluidized bed reactor under various operating conditions

Run	Bed temperature (°C)	Gas velocity (m/s)	Static bed height (cm)	Particle size (μm)	d_{svm} (μm) at 26–30 min[a]
58	100	0.38	21	920.0	38.80
60	100	0.49	21	920.0	33.27
61	100	0.54	21	920.0	18.81
62	100	0.65	21	920.0	14.13

[a] Initial d_{svm} of incinerator ash is 3.14 μm.

increased when operating velocity increased which means the particle size distribution is shifting to larger particles exiting the fluidized bed filter. Although the mechanism of impaction is better for removing large particles at high velocity, but the bounce off for the large particles is also enhanced since the momentum increases. Therefore, large particles were less removed than small ones and d_{svm} increased. Runs 3, 11, 20 and 28 depict the effects of operating bed temperatures on the d_{svm} of particles at outlet of fluidized bed filter. The d_{svm} at outlet increased with an increasing of operating bed temperatures between 36 and 100 °C. When temperature increased, the diffusion raised the capture efficiency for small particles. The increasing gas velocity also caused the larger particles to be bounced off heavily, so the d_{svm} increased. The d_{svm} decreased as bed temperatures raised from 100 to 300 °C. The reason is that as the gas velocity was higher than some critical value, the momentum of the smaller particles could increased and the bounce off increased for smaller particles. The d_{svm} decreased since the small particles exited from the fluidized bed extensively. Furthermore, runs 16, 19 and 22 show the effects of silica sand diameter on removal efficiency of coal ash. The d_{svm} increased as silica sand diameter declined, which meant the higher removal efficiency of submicron particles.

Table 4 lists the d_{svm} of incinerator ash particles at outlet of fluidized bed filter under various operating conditions. Runs 58, 60, 61 and 62 depict the influence of gas velocity on the d_{svm}. The results indicated that the higher operating gas velocity decreased the d_{svm} at outlet which contradicted with the conclusion of coal ash. The segregation existed in the removal of incinerator ash, thereafter the variations of d_{svm} are different to that of coal ash. The small particles are elutriated strongly by segregation since the d_{svm} declined sharply as gas velocity increased from 0.38 to 0.65 m/s. Due to the initial d_{svm} of incinerator ash in the inlet is 3.14 μm, much lower than all conditions in Table 4, the fluidized bed filter seems has high removal efficiency for submicron particles.

4. Conclusion

The major objective of the study focuses on the effect of characteristic of ash and filter media on filtration efficiency during fluidized bed. The performance of the fluidized bed filter for removal of particles in flue gas under various fluidized operating conditions, and then the control mechanisms of particles filtered by fluidized bed were studied. The evaluated parameters included (1) various ashes (coal ash and incinerator ash); (2) bed material diameter; (3) gas velocity; and (4) bed temperature. As above mention, the collection mechanism of coal ash is mainly the inertial impaction. The higher gas velocity and lower bed material size enhance the effect of impaction, the bounce off and elutriation may counteract that on the other hand. The bounce off is very important for the particle filtration if a fluidized bed is applied. The removal efficiency of filtering submicron fly ash by fluidized at high temperature is higher than that at room temperature as diffusion is important at high temperature. The distinction between the characteristics of coal ash and incinerator ash provokes crucial variance in removing particles, so the interparticle and hydrodynamic force acting on fly ash must be understood in advance.

References

[1] B.C. Chiang, M.Y. Wey, C.L. Yeh, Control of acid gases using a fluidized bed adsorber, J. Hazard. Mater. 101B (2003) 259–272.
[2] B.C. Chiang, M.Y. Wey, W.Y. Yang, Control of incinerator organics by fluidized bed activated carbon adsorber, J. Environ. Eng. 126 (11) (2000) 985–992.
[3] B.C. Chiang, M.Y. Wey, W.Y. Yang, C.Y. Lu, Simultaneous control of metals and organics using fluidized bed adsorber, Environ. Technol. 24 (2003) 1103–1115.
[4] D. Geldart, M. Rhodes, Developments in fluidization, Chem. Eng. 2 (1986) 30–32.
[5] C. Tien, Granular Filtration of Aerosols and Hydrosols, Butterworths, London, 1989.

[6] C.S. Chou, C.Y. Tseng, J. Smid, J.T. Kuo, S.S. Hsiau, Numerical simulation of flow patterns of disks in the asymmetric louvered-wall moving granular filter bed, Powder Technol. 110 (2000) 239–245.

[7] S.S. Hsiau, J. Smid, F.H. Tsai, J.T. Kuo, C.S. Chou, Flow patterns and velocity profiles of granules in dorfan impingo filters for gas cleanup, Chem. Eng. Sci. 55 (2000) 4481–4494.

[8] S.S. Hsiau, J. Smid, F.H. Tsai, J.T. Kuo, C.S. Chou, Velocities in moving granular bed filers, Powder Technol. 114 (2001) 205–212.

[9] P. Knettig, J.M. Beeckmans, Capture of monodispersed aerosol particles in a fixed and in a fluidized beds, Can. J. Chem. Eng. 52 (1974) 703–706.

[10] Y. Doganoglu, V. Jog, K.V. Thambimuthu, R. Clift, Removal of fine particles from gases in fluidized beds, Trans. IChemE 56 (1978) 239–248.

[11] G. Tardos, N. Abuaf, C. Gutfinger, Diffusion filtration of dust in a fluidized-bed, Atmos. Environ. 10 (1976) 389–394.

[12] M.H. Peters, L.-S. Fan, T.L. Sweeny, Simulation of particulate removal in gas-solid fluidized beds, AIChE J. 28 (1982) 39–49.

[13] K. Ushiki, C. Tien, Calculation of aerosol collection in fluidized filter beds, AIChE J. 30 (1984) 156–168.

[14] K. Ushiki, C. Tien, Aerosol collection in the jet region of fluidized filters, AIChE J. 32 (1986) 1606–1611.

[15] M. Ghadiri, J.P.K. Seville, R. Clift, Fluidized-Bed Filtration of Gases at High Temperatures, Trans IChemE 71A (1993) 371–381.

[16] S.T. Pemberton, J.F. Davidson, Elutriation from fluidized-beds. 2. Disengagement of particles from gas in the freeboard, Chem. Eng. Sci. 41 (1986) 253–262.

[17] K. Smolders, J. Baeyens, Elutriation of fines from gas fluidized beds: mechanisms of elutriation and effect of freeboard geometry, Powder Technol. 92 (1997) 35–46.

[18] J.H. Choi, K.B. Choi, P. Kim, D.W. Shun, S.D. Kim, The effect of temperature on particle entrainment rate in a gas fluidized bed, Powder Technol. 92 (1997) 127–133.

[19] J.H. Choi, J.M. Suh, I.Y. Chang, D.W. Shun, C.K. Yi, J.E. Son, S.D. Kim, The effect of fine particles on elutriation of coarse particles in a gas fluidized bed, Powder Technol. 121 (2001) 190–194.

[20] S.M. Tasirin, D. Geldart, Entrainment of FCC from fluidized beds – a new correlation for the elutriation rate constants $K^*_{i\infty}$, Powder Technol. 95 (1998) 240–247.

[21] X. Ma, K. Kato, Effect of interparticle adhesion forces on elutriation of fine powders from a fluidized bed of a binary particle mixture, Powder Technol. 95 (1998) 93–101.

[22] J. Li, K. Kato, A correlation of the elutriation rate constant for adhesion particles (group C particles), Powder Technol. 118 (2001) 209–218.

[23] S.E. George, J.R. Grace, Entrainment of particles from a pilot scale fluidized bed, Can. J. Chem. Eng. 59 (1981) 279–284.

[24] D. Geldart, A.C.Y. Wong, Entrainment of particles from fluidized beds of fine powders, AIChE Symp. Ser. 83 (255) (1987) 1–9.

[25] T. Baron, C.L. Briens, J.D. Hazlett, M.A. Bergougnou, P. Galtier, Size distribution of the particles entrained from fluidized-beds-gas humidity effects, Can. J. Chem. Eng. 70 (1992) 631–635.

[26] J. Baeyens, D. Geldart, S.Y. Wu, Elutriation of fines from gas-fluidized beds of geldart A-type powders – effect of adding superfines, Powder Technol. 71 (1992) 71–80.

[27] J.M. Rodríguez, J.R. Sánchez, A. Alvaro, D.F. Florea, A.M. Estévez, Fluidization and elutriation of iron oxide particles. a study of attrition and agglomeration processes in fluidized beds, Powder Technol. 111 (2000) 218–230.

[28] C.Y. Wen, Y.H. Yu, Mechanics of fluidization, Fluid Particle Technol. Chem Eng. Progr. Symp. Ser. 62 (1966) 100–111.

[29] M.E. Fayed, L. Otten, Handbook of Powder Science and Technology, Chapman & Hall, New York, 1997.

[30] A. Lozano, V. Henriquez, A.M. Machin, Modelling of a new cross-flow moving-bed heat-exchanger/filter (MHEF), Filtration Separat. 33 (1996) 69–74.

[31] S.Y. Wu, M.F. Su, J. Baeyens, The fluidized bed pyrolysis of shredded tyres: the influence of carbon particles, humidity, and temperature on the hydrodynamics, Powder Technol. 93 (1997) 283–290.

[32] M.G. Rasul, V. Rudolph, F.Y. Wang, Particles separation using fluidization techniques, Int. J. Miner. Process. 60 (2000) 163–179.