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Effect of particle size on flotation performance of incinerator fly ash

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ABSTRACT

In this study, to understand the effect of particle size on the flotation of medical waste incinerator (MWI) fly ash, we investigated flotation of fly ash as applicable to five particle-size categories, namely 0–25, 25–38, 38–75, 75–106, and 106–250 μm. We employed both conventional flotation cell (CFC) and cyclonic-static micro bubble flotation column (FCSMC). The results revealed that small particle fly ash (0–38 μm) enriched with powder-activated carbon contained relatively high quantities of low-chlorinated dioxins. For the finest particles (0–25 μm), with CFC, mass recovery was high and carbon and dioxin recovery efficiencies were low. For most size fractions, carbon removal efficiency with FCSMC was higher than that with CFC. After flotation with CFC, the loss on ignition of the tailings from the finest particles (0–25 μm) and the coarsest particles (106–250 μm) was >6%. Additionally, the total toxic equivalent (TEQ) of dioxins in the tailings from small particles (0–38 μm) was >3 ng I-TEQ g^{-1}. However, with FCSMC, the TEQ of dioxins in the tailings from all particle-size fractions met the standards. Thus, MWI fly ash with particle size <38 μm cannot be suitably treated with CFC and should be treated with FCSMC.

Keywords: Fly ash; Flotation; Particle size; Powder-activated carbon; Dioxins

1. Introduction

Incineration is one of the most effective and extensive treatment methods of medical waste [1]. However, incineration generates and enriches dioxins in the end products, such as flue gas and fly ash. Generally, flue gas can be safely emitted into the environment after purification with a combination of powder-activated carbon (PAC) injections and baghouse filtration. After the adsorption of dioxins on PAC, the PAC is collected in a bag filter and becomes a part of medical waste incinerator (MWI) fly ash. Parts of dioxins are also adsorbed on the surface of unburned carbon in the MWI fly ash [2]. Thus, the carbonaceous matter, including PAC and unburned carbon, are considered major sources of dioxins in MWI fly ash [3]. Therefore, efficient techniques for carbon recovery from MWI fly ash are very important.

Since the 1970s, the methods of flotation to separate the carbon from fly ash were published [4]. Flotation is a physicochemical separation process in which gas bubbles are added to liquid; contaminants form a suspension according to the hydrophobic and hydrophilic characteristics of different materials, which has been applied not only in the mineral industry, but also pulp mills, rubber, waste battery, and environmental engineers due to its advantage include the requirement of less physical space, less power and a greater ability to recover valuable fines. Flotation can remove some dioxins enriched in the carbonaceous matter because they exhibit the proper lipophilic and hydrophobic

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nature; therefore, two types of matter can be simultaneously removed from MWI fly ash with flotation [5]. After flotation, most dioxins and carbonaceous matter can be enriched into the froth products. Furthermore, the froth materials can be reburned as an auxiliary fuel for the MWI process; such as reburning can decompose the dioxins [6]. Many factors affect flotation behavior, such as chemical reagents (collectors, frothers, and surfactants), operating parameters, and feed characteristics [7,8]. In our previous study, we reported a comparison between the decarburization effect of MWI fly ash with conventional flotation cell (CFC) and cyclonic-static micro bubble flotation column (FCSMC) methods. We determined the optimal conditions of two different flotation devices; however, we did not investigate the effect of particle characteristics of fly ash on flotation.

Flotation is a highly complex process based on the attachment of particles to air bubbles, and this process is determined in terms of the most critical steps of contact, breakdown of hydration film, and overcoming the shedding force [9,10]. Therefore, the particle size of raw materials is a crucial parameter. Many researchers have investigated the importance of particle size for flotation. Zhang and Honaker [11] indicated that carbon recovery of −25 μm fractions is higher than that of +25 μm fractions because coarse carbon has complicated porous structures that fill with water, but fine carbon particles have flat surfaces. Cheng et al. [12] concluded that as the coarseness of the particles increases, the less combustible matter is recovered. Huang et al. [13] determined that the removal efficiency of small and medium fly ash particles was higher than that of large fly ash particles. Cheng et al. [12] revealed that coarse coal has adequate selectivity and a slow flotation rate; by contrast, coal with fine particles has poor selectivity and a high flotation rate. Xia et al. [14] detected that floating large oxidized coal particles was more difficult than floating fine particles because capturing large oxidized coal particles with bubbles was difficult because they easily detached from the bubbles. Decreasing particle size may enhance the flotation performance of oxidized coal. Zhang et al. [10] proved that the relationship between combustible matter recovery and particle size outlines an "elephant" shape, and detected the coal flotation performance of both coarse and fine particles to be remarkably poor. Therefore, particle-size distribution greatly affects flotation kinetics.

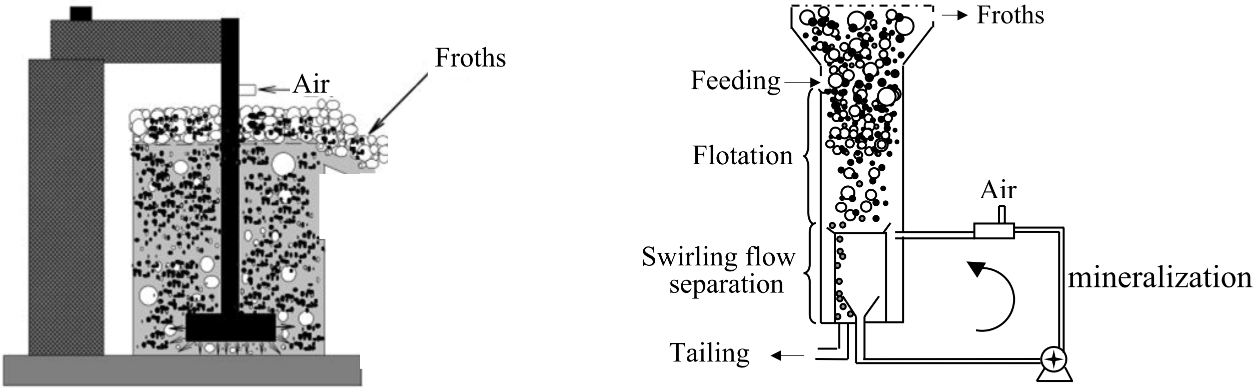
For different flotation devices, particle-size distribution greatly influences the flotation process. Generally, in the case of CFC, particles that can be floated efficiently are in the size range of 10–200 μm and the optimal range is 20–50 μm [8]. Two major particle transportation mechanisms of flotation and mechanical entrainment exist during the flotation process with CFC. The first is a selective process related to particle–bubble attachment and detachment. The second contributes to the nonselective transportation of fine particles in the froths, which is primarily related to the particle-size distribution and hydrodynamic parameters [8]. The flotation columns are not mechanically agitated; thus, the hydraulic entrainment can be reduced because of the geometry and hydrodynamic characteristics of the columns [15]. In particular, FCSMC can efficiently promote the separation of microfine particles by generating microbubbles and ensuring continuous circulation within the column. Li et al. [16] detected that by with the FCSMC method, more MgO can be removed from −10 μm sized fractions. Therefore, the contribution of true flotation and entrainment with both CFC and FCSMC methods must be assessed by analyzing the effect of particle size (Fig. 1).

The distribution of carbon and dioxins according to particle-size fractions may also affect the flotation of MWI fly ash. The flotation behavior of five types of size fractions of incinerator fly ash has not been sufficiently investigated. In this study, the effect of the particle size of fly ash on the flotation performance was investigated with 0–25, 25–38, 38–75, 75–106, and 106–250 μm particle-size fractions. The purpose of this study was to understand the effect of different sizes on the partitioning of dioxins during flotation.

2. Materials and method

2.1. Materials

The fly ash sample was used in the study was collected from a gyration kiln incinerator in southern China, which capacity is 15 t d^{-1}. The ash sample was collected from



(a) CFC (b) FCSMC

Fig. 1. Flotation device diagram of CFC and FCSMC.

the hopper of the bag filter, so it contained PAC injected before being filtered by the baghouse. The ash sample in this study subjected to weathering for 6 months. After collection, the ash sample was homogenized and sieved to remove large particles by a 60 mesh (250 μm) of the sifter, and dried at 105°C for 24 h. Loss on ignition (LOI) was determined as the weight loss of the subsample in the condition of 3 h and 1,023 ± 25 K [17]. The main compositions of the ash are shown in Table 1.

2.2. Methods

The ash sample was sieved into five different fractions (i.e., 0–25, 25–38, 38–75, 75–105, and 106–250 μm) by using a stainless steels screen with openings of 150, 200, 400, and 500 mesh [18]. The weight distribution and the content of dioxins and carbonaceous matter in each fraction were determined. The flotation of five different particle-size fractions of the MWI fly ash was investigated. Experiments were carried out using a CFC and FCSMC, respectively, which were the same as those in our previous study [19]. CFC device is a 1 L of CFCs (RK/FD111, Rock Crush & Grand Equipment Manufacture Co., Ltd., Wuhan, China), FCSMC device (R50–2000, China University of Mining and Technology, Xuzhou, China) has a section diameter of 50 mm, a height of 1,500 mm and a working volume of 3.8 L. For CFC, the parameter of kerosene, methyl isobutyl carbinol (MIBC), Tween 80 and slurry were 3 and 0.1 g kg^{-1} ash, 5% and 100 g L^{-1}, respectively, while the impeller speed was 2,000 rpm. To compare the flotation performance of different particle sizes, all flotation parameters are consistent. For FCSMC, the kerosene dosages were 3.5 g kg^{-1} ash while the MIBC dosage 0.2 g kg^{-1} ash, Tween 80 percentage 7.5%, the slurry concentration was 100 g L^{-1}, circulation pump speed was 380 r min^{-1}. Froths and the tailings after the flotation of each particle-size fractions were analyzed separately to determine LOI and the content of dioxins.

In order to evaluate the flotation performance of each particle-size fraction, the following parameters were evaluated: removal efficiency of carbon (Eq. (1)) and removal efficiency of dioxins (Eq. (2)).

Table 1
Major characteristics of raw incinerator fly ash

Major compounds	Mass fraction (%)
SiO_2	14.31
CaO	23.55
Al_2O_3	3.65
Fe_2O_3	3.31
MgO	1.09
K_2O	4.58
Na_2O	17.03
SO_3	4.83
Cl	22.38
TiO_2	0.99
F	1.19
LOI	15.84
IC	1.14

$$\text{Carbon recovery efficiency}(\%) = \frac{\text{Carbon}_{\text{Froths}} \times \text{Mass}_{\text{Froths}}}{\left(\begin{array}{l}\text{Carbon}_{\text{Froths}} \times \text{Mass}_{\text{Froths}} + \\ \text{Carbon}_{\text{Tailings}} \times \text{Mass}_{\text{Tailings}}\end{array}\right)} \tag{1}$$

$$\text{Dioxin recovery efficiency}(\%) = \frac{\text{Dioxin}_{\text{Froth}} \times \text{Mass}_{\text{Froth}}}{\left(\begin{array}{l}\text{Dioxin}_{\text{Froths}} \times \text{Mass}_{\text{Froths}} + \\ \text{Dioxin}_{\text{Tailings}} \times \text{Mass}_{\text{Tailings}}\end{array}\right)} \tag{2}$$

where $\text{Carbon}_{\text{Froths}}$ is the mass fraction of carbon in the froths, in %; $\text{Mass}_{\text{Froths}}$ is the mass of froths, in g; $\text{Carbon}_{\text{Tailings}}$ is the mass fraction of carbon in the tailings, in %; $\text{Mass}_{\text{Tailings}}$ is the mass of tailings, in g.

3. Results and discussion

3.1. Distribution of carbon and dioxins in different particle-size fractions

Table 2 shows the weight distribution and carbon contents (i.e., LOI) of different particle-size fractions of fly ash. The granularity distribution of the fly ash was mostly concentrated in the smaller particle size range, in which 0–25 μm particles occupy 7.54%, and 25–38 μm particle size accounts for 44.82%, 38–75 μm is 34.31%, while 75–106 μm, 10.18%, and others (106–250 μm) only 3.15%. The fractions of the fly ash in the range of 0–75 μm accounted for 86.67 wt.% of the total quantity, which is an optimal particle size range for flotation [8]. The particle size of MWI fly ash in our physical experiments was much finer than that of municipal solid waste incinerator (MSWI) fly ash reported in the literature [5,20]; this difference might be attributed to different feeding wastes, incinerator types, and air pollution control devices. Compared with reports from the literature, in this study, the carbon content in fine particles was higher, the overall LOI of the fly ash was 15.84%, and the LOI of 0–25 μm fractions was 23.15%. This may be attributed to the PAC enriched in finer fractions; according to our previous study, 74.36% of PAC was in the 0–38 μm size range [18]. Unburned carbon mainly consisted of black flake charcoal and may be present as large particles in fly ash [13].

The total dioxin content in the fly ash particles of size 0–25 μm was 148.22 ng g^{-1}, which was more than twice the content of particles of size 106–250 μm. The particle-size distribution of dioxins was similar to that of carbon (Table 2). Fig. 2 shows the content of different dioxin congeners for all particle-size fractions of fly ash. A negative correlation was observed between size particle fractions and dioxin content because the higher surface area of fine fractions (compared with coarser fractions) increased the adsorption of dioxins. Lu also found dioxins are concentrated in the fine fraction of fly ash, because a smaller particle has higher specific surface

Table 2
Mass distribution, LOI, carbon distribution, dioxins content and distribution of each size fractions

Particle-size fraction	Mass distribution (%)	LOI (% by wt.)	Carbon distribution (%)	Dioxin content (ng g^{-1})	Dioxin distribution (%)
0–25 μm	7.54	23.15	11.03	148.22	11.17
25–38 μm	44.82	16.19	45.84	108.12	48.45
38–75 μm	34.31	14.58	31.60	87.83	30.13
75–106 μm	10.18	14.12	9.08	81.94	8.34
106–250 μm	3.15	12.33	2.45	61.80	1.95

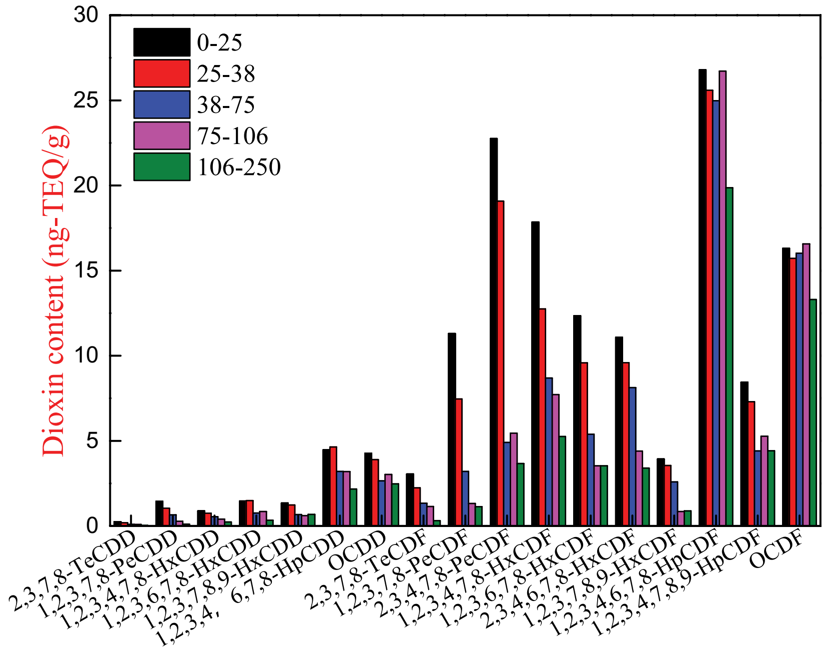


Fig. 2. Dioxin levels in fly ash categories.

area, thus offering more adsorption sites [21]. Huang also proved that the small particle-size fractions (0–44 μm) contain more polychlorinated biphenyls (PCBs) than the large particle-size fractions because PCBs are more easily adsorbed on small particles [22,23]. In addition, the dioxins were remarkably enriched in small fractions. This can be attributed to enrichment with numerous low-chlorinated dioxins, such as TeCDF, PeCDF, HxCDF, and PeCDD, in PAC, and most of the PAC particles were in the 0–25 and 25–38 μm size ranges. Therefore, low-chlorinated dioxin homologs were concentrated in the fine size categories of fly ash. The total dioxin content in fly ash was 78.8 ng g^{-1}, which was equivalent to 6.98 ng I-TEQ g^{-1} (TEQ – total toxic equivalent).

3.2. Effect of particle size on mass recovery

Fig. 3 presents the effect of particle size on mass recovery with the CFC and FCSMC methods. In case of CFC, the mass recovery increased from 41.6% to 65.8% as the particle size decreased. The finest particles (0–25 μm) were not attached to air bubbles and were unselectively carried into the froths; because these fine particles entered the froth, the mass recovery of the finest particles (0–25 μm) was particularly high. Primarily, these particles were recovered with hydraulic entrainment instead of true flotation. The coarse particles (106–250 μm) easily drained back into the pulp during flotation because the particle–bubble attachment was low and the air–bubble capacity to carry these coarse particles was limited [8].

In the FCSMC method, nanobubbles in the flotation slurry were used to reduce the detachment of coarse particles and to increase the probability of bubble–particle attachment. Concurrently, the entrainment was less. Therefore, the particle size did not considerably affect the mass recovery.

3.3. Effect of particle size on the decarburization efficiency

Fig. 4 shows the effect of particle size on carbon removal in two different flotation devices. In case of CFC, the carbon removal efficiency (CRE) was high (>91%) for 25–106 μm fractions; however, it was low for fractions with the largest (106–250 μm) and the smallest (0–25 μm) particle-size fractions. This result is consistent with the results of a soil

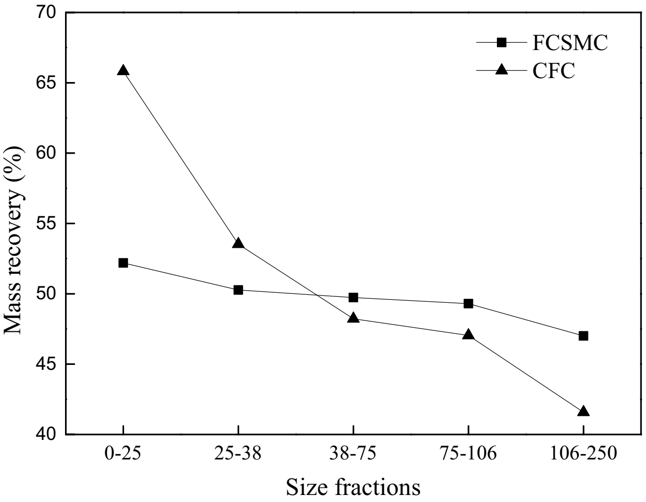


Fig. 3. Effect of particle size on mass recovery by CFC and FCSMC.

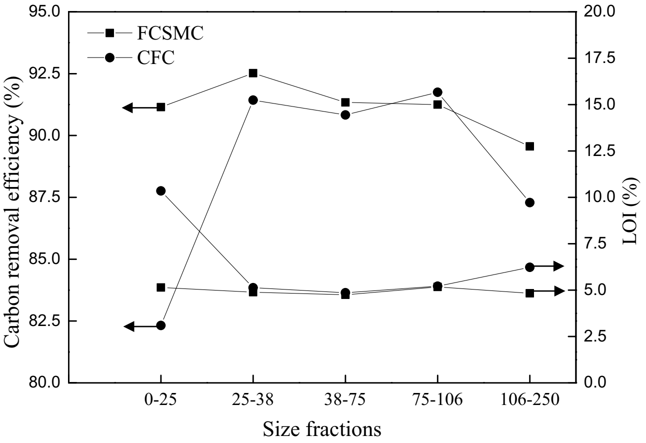


Fig. 4. Effect of particle size on carbon removal and LOI by CFC and FCSMC.

flotation study by Dermont et al. [8]. They obtained the best flotation efficiency with intermediate particle-size fractions. A combined effect of collision and attachment/detachment subprocesses for particle-size fractions can explain these results. The high CRE with 25–106 μm particles may be related to the high collision and attachment probabilities between the particles and the air bubbles. The low momentum and low probability of collision of excessively fine particles with bubbles resulted in low attachment, and thus, a low CRE; allegedly, bubble–particle detachment is usually neglected. The high detachment probability of coarse particles (106–250 μm) from the bubble surface is a result of the particle weights and turbulence eddies, and it leads to poor flotation selectivity [10].

The curves in Fig. 4 demonstrate that CRE for most sizes of fractions with FCSMC was clearly higher than that with CFC. In particular, CRE for the finest particles (0–25 μm) with CFC was only 82.3%. Particle fractions <25 μm exhibited a microfine particle flotation problem, as mentioned in the previous section. Nonselective entrainment of the finest particles caused particles to float to the froth zone, which decreased the carbon content in the froth product [8,14]. This impedes true flotation of the lowest particle-size fractions (0–25 μm), and thereby reduces CRE. By contrast, with FCSMC, more carbon was removed from the 0–25 μm sized fractions by efficient mineralization of the microfine particles in the feed [16]. Therefore, the change of CRE for all particle-size ranges by FCSMC is not evident. In case of FCSMC, the highest CRE occurred in the particle-size range of 25–38 μm, which may be because of small particles (−38 μm) enriched with PAC. PAC is less affected by weathering and is probably more hydrophobic.

Fig. 4 also presents the influence of particle size on LOI in the cleaned tailings with two different flotation devices. In case of CFC, LOIs of the tailings with the finest particles (0–25 μm) and the coarsest particles (106–250 μm) were almost 10.4% and 6.23%, respectively, both of which exceed the American Society for Testing Material specification of 6.0% LOI in fly ash. For FCSMC, the LOIs of the tailings with all particle sizes were lower than those for CFC.

3.4. *Effect of particle size on dioxin removal efficiency*

The removal efficiency values of dioxin homologs for different particle sizes after flotation with CFC and FCSMC methods are depicted in Figs. 5 and 6, respectively. Relative to FCSMC, the removal efficiency of all dioxin homologs in small particles (0–38 μm) changed considerably when CFC was used. The removal efficiencies of the low-chlorinated congeners (tetra- to hexa-dioxins) were almost 90% and those of 1,2,3,4,6,7,8-HpCDD, OCDD, 1,2,3,4,,6,7,8-HpCDF, and OCDF were <84%. This may be attributed to the removal of PAC during the flotation process. Gaseous-phase dioxins in the flue gas were easily adsorbed on the porous PAC, and these low-chlorinated dioxins were strongly attached to the PAC during flotation decarburization.

In addition, some dioxins in the MWI fly ash were removed with dissolution–adsorption flotation; the removal mechanism included three steps (Fig. 7): (1) *dissolution*: some dioxins deviated from the solid matrix and some were solubilized by the addition of surfactant mixtures; (2) *adsorption*: dioxins in the solution were adsorbed in the carbonaceous matter because of its effective adsorption property; (3) *flotation*: dioxins combined with carbonaceous matter were carried from the solution into the froth materials through flotation; during this process, the carbonaceous matter acted as a carrier of dioxins [24]. Because of their high hydrophobic property, dissolved dioxins are easy to remove with adsorption flotation; however, the differences between the aqueous solubility and molecular size of different chlorinated congeners may also affect the removal efficiency of individual dioxin congeners [25]. Flotation is a highly complicated physicochemical process related to the nature of the dioxin congeners and the bubble–particle collision efficiency in the flotation process [26]. Additional research is required to investigate the difference in the removal efficiencies of different dioxin congeners in fly ash.

Dioxins removal efficiency (DRE) values and the TEQs of dioxins in the tailings of different particle-size fractions are shown in Fig. 8. In case of CFC, the DRE of medium-size particles (25–106 μm) was high; a similar trend was observed for the CRE. DRE of the finest particles (0–25 μm) was

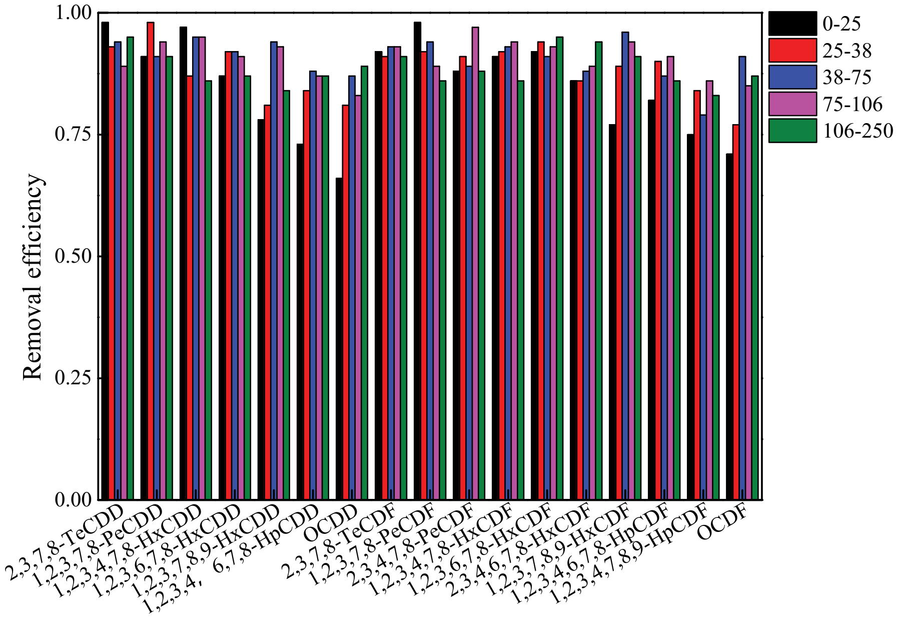


Fig. 5. Removal efficiency levels of each dioxin congener with CFC.

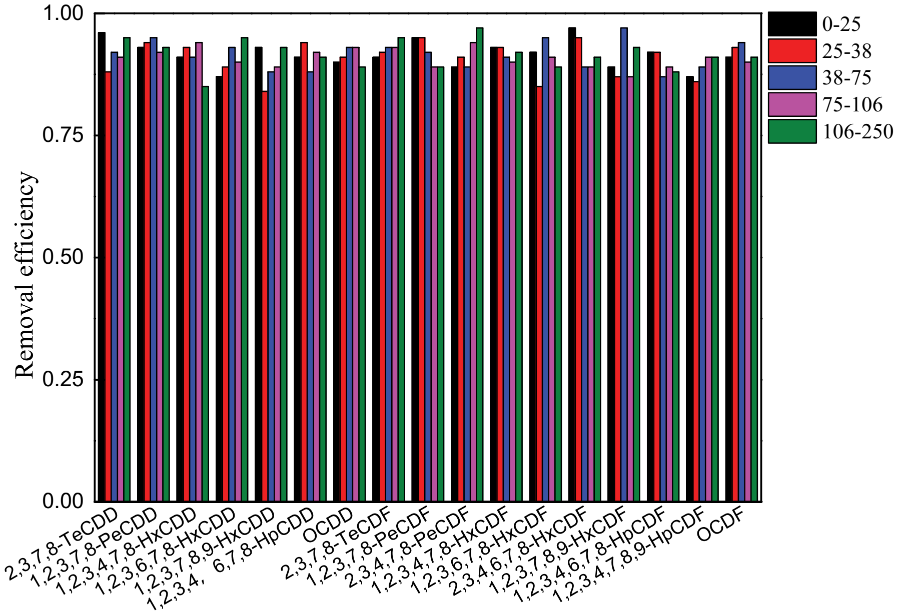
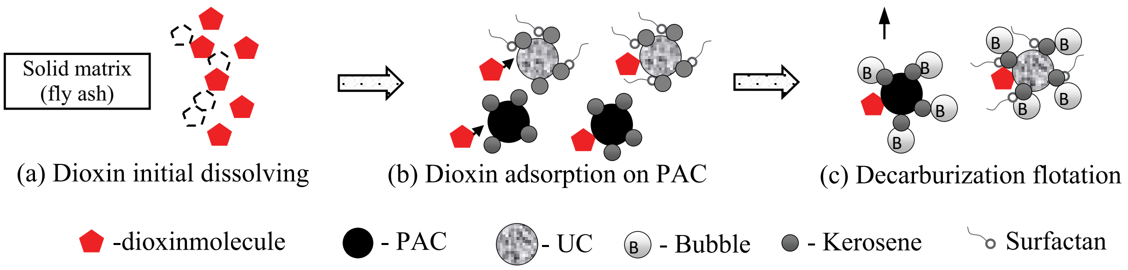


Fig. 6. Removal efficiency levels of each dioxin congener with FCSMC.

relatively low because of the serious entrainment during the flotation process. In case of CFC, the selective separation of hydrophobic particles and hydrophilic particles is particularly ineffective in this particle range [8]. Low DRE of the coarsest particles (106–250 μm) may be attributed to their low initial dioxin contents and shedding probability. Fig. 8 illustrates that the amounts of dioxins removed with FCSMC were higher than that removed with CFC for particles of the same size, except for 38–75 μm particles. FCSMC employed a self-absorbing microbubble generator to generate microbubbles, which considerably improved the flotation recovery of hydrophobic particles by increasing the probability of collision and attachment and by reducing the probability of detachment during the flotation [26]. This indicates that introducing microbubbles into the column flotation system in FCSMC was highly efficient for the fine and coarse particle fractions.

Fig. 8 shows that for a landfill in China, with CFC, the TEQs of dioxins in the tailings with fine particles measuring 0–25 and 25–38 μm were almost 3.92 and 3.21 ng I-TEQ g^{-1}, respectively; these values were more than the regulation limit (3 ng I-TEQ g^{-1}) [27]. This may be attributed to the



(a) Dioxin initial dissolving (b) Dioxin adsorption on PAC (c) Decarburization flotation

Fig. 7. Conceptual diagram of dioxins removal regarding interactions among dioxins, PAC, UC, bubble and kerosene during flotation.

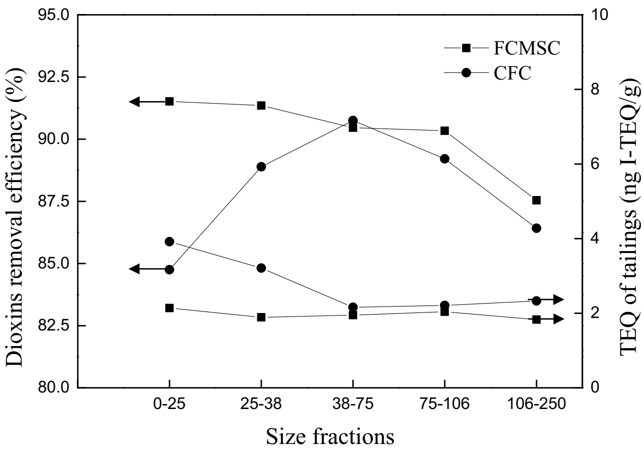


Fig. 8. Effect of particle size on dioxins removal and TEQ of tailings by CFC and FCSMC.

high dioxin content in fly ash with fine particles, especially low-chlorinated dioxins. The low-chlorinated dioxins exhibited a relatively high toxicity factor, which may explain the high TEQ values for the tailings from fine fly ash particles [18]. Therefore, in case of CFC, for the removal of dioxins, fractions smaller than 38 µm should be particularly considered. In case of FCSMC, the dioxin content of all tailings met the standards.

4. Conclusions

In this study, we used FCSMC and CFC to investigate the flotation behavior of MWI fly ash as applicable to five particle sizes. Particles of size 0–25 µm had the highest LOI and the highest dioxin content. The mass recovery increased with the decrease of particle size for CFC but did not change significantly with particle size for FCSMC. The CREs for the finest particles (0–25 µm) with CFC and FCSMC were 82.3% and 92.5%, respectively. In addition, the LOIs of the tailings with the finest (0–25 µm) and the coarsest (106–250 µm) particles with CFC were almost 10.4% and 6.23%, respectively; all these values were higher than those obtained with FCSMC. In case of CFC, the TEQ of dioxins in the tailings after the flotation of small particle fractions (0–38 µm) was >3 ng I-TEQ g^{-1}. However, the dioxin content of all tailings with FCSMC met the landfill standards. Therefore, small particles (<38 µm) cannot be suitably treated with CFC and should be treated with FCSMC.

Acknowledgments

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