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Removal of PCDDs/Fs from municipal solid waste incineration by entrained-flow adsorption technology*

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Abstract: Entrained flow adsorption using activated carbon as the adsorbent is widely adopted for PCDDs/Fs-abatement in municipal solid waste incineration (MSWI) process. The effects of operating parameters including flue gas temperature, feeding rate of activated carbon, polychlorinated dibenzodioxins and polychlorinated dibenzofurans (PCDDs/Fs) concentration at the inlet of the air pollution control device (APCD), filter materials, pressure drop on PCDDs/Fs removal efficiency are reviewed and commented upon in this paper. Evaluation on the various mechanistic models for entrained flow adsorption is carried out based on the computational simulation in terms of the actual operating condition and theoretical analysis. Finally, an advancement of entrained flow adsorption in combination of dual bag filter is introduced.

Key words: PCDDs/Fs, Entrained flow adsorption, Operating parameters, Mechanistic model, Dual bag filters
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INTRODUCTION

Polychlorinated dibenzodioxins and polychlorinated dibenzofurans (PCDDs/Fs) are some major toxic substances unintentionally produced mainly from municipal solid waste incineration (MSWI). Attention has been focused on the best way for controlling and regulating such emissions. Among flue gas treatment technologies for post combustion zone emission control (Buekens and Huang, 1998; McKay, 2002), activated carbon adsorption (ACA) and techniques involving physical adsorption are widely employed for removing PCDDs/Fs and some other toxic substances, such as Hg and other heavy metals from flue gas. ACA is generally classified into three types: entrained-flow, fixed-bed and moving-bed (Everaert and Baeyens, 2004; Kilgroe, 1996). The performance characteristics of the three systems are shown in Table 1. The technology of entrained-flow adsorption is the focus of this work.

TECHNICAL BACKGROUND OF ENTRAINED-FLOW ADSORPTION

Entrained-flow adsorption

PCDDs/Fs exist both in the gas phase and solid phase in combustion flue gases. The gas/particle partitioning of PCDDs/Fs changes as the flue gas flows through the MSWI system (Smolka, 1997). The flue gas temperature, particle concentration and particle properties such as pore size and chemical composition of the fly ash are major factors affecting the gas/solid ratio of PCDDs/Fs. At the filter bag, gaseous fraction of PCDDs/Fs can be more than 50%. The flue gas temperature is another factor determining the ratio of gas phase PCDDs/Fs to solid phase PCDDs/Fs. In the process of entrained flow, activated carbon powder is injected in front of the filter bag, and flue gases pass through the activated cake accumulated on the filter bag surface. Thus, PCDDs/Fs and other toxic gaseous

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Table 1 Removal of PCDDs/Fs from flue gases by combination of bag filter and activated carbon adsorption

Process	Equipment	Performance data
Entrained-flow	Wet scrubber, bag filter with AC injection (trade name of AC: sorbalit); fabric filter (T=120 °C) with AC injection (90% of the AC residue from the filter are re-circulated to the injection point)	PCDD/F in (a) untreated gas: 2.17 ng TEQ/Nm^3; (b) purified gas: 0.069 ng TEQ/Nm^3; removal: 96.8%; AC dosage: 50 mg/Nm^3; PCDD/F (a) before filter: 0.24 ng TEQ/Nm^3; (b) after filter: 0.01 ng TEQ/Nm^3; removal: 95.8%
Fixed-bed	MEDISORBON/KOMBISORBON adsorber (a mixture of zeolit, carbon and inert material; flue gas inlet temperature: 40~100 °C)	AC consumption: the whole bed is replaced after a few years; PCDD/Fs in (a) raw gas: 0.3 ng TEQ/Nm^3; (b) clean gas: 0.05 ng TEQ/Nm^3; removal: 83% (after 23100 h test duration)
Moving-bed	WKV/integral counter-current activated coke process (flue gas inlet temperature: 120~165 °C); moving-bed adsorber (flue gas inlet temperature: 150 °C): space velocity: 1000 h^{-1}	AC consumption: 500 ton per year per plant, total gas flow: 464×10^3 Nm^3/h; PCDD/F stack emission: 0.015 ng TEQ/Nm^3; AC consumption: 5 mm of bed height per day; PCDD/F in (a) feed gas: 100 ng/Nm^3; removal: 98.8%

substances are removed from flue gas. The gas phase fraction that passes through the filter bag and is released to the atmosphere is the contaminating source harming the environment. The PCDDs/Fs particles fraction attached on the surface of solid particle such as fly ash is removed by the filter bag. Injection of an absorbent such as activated carbon can transform the gas phase PCDDs/Fs into solid phase by adsorption. Injection of powdered activated carbon (PAC) increases the load on the bag filter surface, and consequently affects the filter bag pressure drop, which is an important factor indicating PCDDs/Fs removal in MSWI flue gas treatment.

Advantages and disadvantages

Activated carbon adsorption using a bag filter system has many advantages, i.e. easy handling, effectiveness, and low capital cost, although conventional activated carbon adsorption using a single bag filter (SBF) system can result in high carbon consumption because of the low (less than 3%) utilization efficiency (Kim and Kim, 2004) of activated carbon (>150 mg/Nm^3), and the difficulty to meet the more stringent emission standard of PCDDs/Fs (0.1 ng TEQ/Nm^3, at 12% O_2), so that the conventional SBF process must be modified to be more effective.

EFFECTS OF CARBON INJECTION CONDITION ON PCDDS/FS REMOVAL EFFICIENCY

Correlation between flue gas temperature and removal efficiency

Table 2 shows that the vapor pressure of PCDDs/Fs homologue decreases with increasing chlorination at 25 °C (McKay, 2002), hence the high chlorination homologues generally occur in solid form such as OCDD and OCDF, as low chlorination homologues likely to stay in the gas phase. The bag filter can hold the major part of the solid phase PCDDs/Fs and a small fraction of the gas phase PCDDs/Fs deposited on and inside the bag filter (Mätzing *et al*., 2001). Without injection of AC into the flue gas, the removal efficiency of BF decreased rapidly from 97.76% to 75.42%, with the flue gas temperature increasing from 160 °C to 220 °C (Tejima *et al*., 1996). It can be explained that as the saturated vapors of PCDDs/Fs decreases with increasing flue gas temperature, a portion of the PCDDs/Fs adsorbed in the solid phase is hence released into gas phase. Milligan and Altwicker (1996) that reported incinerator fly ash has about 1×10^{-5} mol/g of adsorption sites. While, the number of AC adsorption sites is 2 orders of magnitude higher than that of fly ash. Fig.1 shows that as temperature increases, the fractional surface coverage deceases due to the adsorption/desorption equilibrium (McKay, 2002). So, the removal efficiency of BF for PCDDs/Fs declines with increasing flue gas temperature.

Table 2 Vapor pressure of PCDDs/Fs Homologue group

Homologue group	Vapor pressure (Pa at 25 °C)	Congeners No.
TCDD	1.08E−04	22
PeCDD	9.73E−08	14
HxCDD	7.87E−09	10
HpCDD	4.27E−09	2
OCDD	1.11E−10	1
TCDF	3.33E−06	38
PeCDF	3.60E−07	28
HxCDF	3.73E−08	16
HpCDF	1.32E−08	4
OCDF	5.07E−10	1

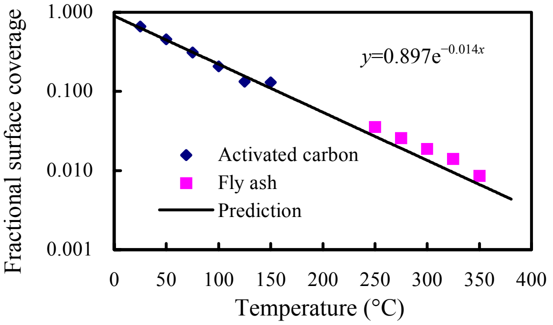


Fig.1 Effect of temperature on coverage of adsorption site

Temperature is an important parameter in the PCDDs/Fs removal process, with low flue gas temperature making gas phase PCDDs/Fs adsorption more effective. However, water vapor in the flue gas is condensed below the acid dew point (of <140 °C) should be avoid in order to minimize the damages caused by the increase of pressure drop across the filter bag. Thus, preheating is needed to avoid such condensation, and the bag filter operating temperature must be kept over 145 °C under continuous operation.

With addition of AC into flue gas, the removal efficiency for PCDDs/Fs remains steadily within a high value range of 95% to 98% when the temperature is held between 160 °C to 190 °C (Fig.2), it decreases slightly to 90% at the flue gas temperature of 220 °C (Kim and Kim, 2004; Tejima *et al*., 1996). It is the adsorption property of AC that determines that the major part of the gas phase PCDD/Fs is adsorbed by AC, then to be removed by BF, while, the adsorptive capacity is also weakened by higher temperature, which will cause a small decrease of removal efficiency.

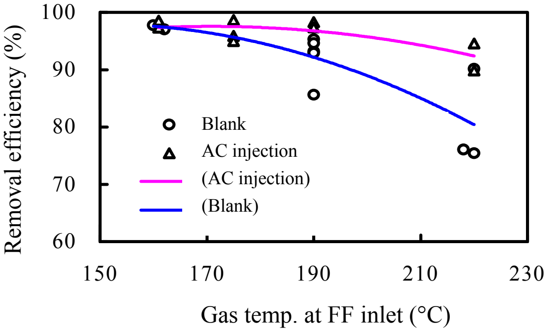


Fig.2 Relationship between FF inlet gas temperature and PCDDs/Fs removal efficiency (Kim and Kim, 2004; Tejima *et al*., 1996)

To weight the various factors (such as durability of filter material, operating costs, etc.), operating temperature of flue gas at inlet of BF is recommended to be held within 150 °C to 180 °C as optimal parameter.

Effect of the AC feeding rate on removal efficiency

It is reported in some literature (Buckens and Huang, 1999; McKay, 2002) that 50~100 mg/Nm^3 of AC concentration can bring about good removal efficiency, although there are no detailed data to support this opinion. Kim and Kim (2004) conducted tests on the feeding rate of AC on removal efficiency. In the SBF system, PCDDs/Fs removal efficiency increased at the beginning when the AC concentration increased as shown in Fig.3. However, no considerable improvement was detected when higher than 150 mg/Nm^3 of AC was used. Furthermore, removal efficiency decreased at AC feeding rate >300 mg/Nm^3.

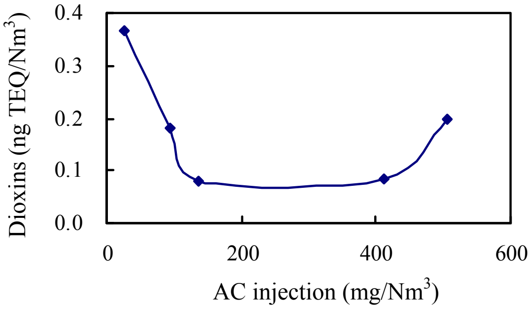


Fig.3 Relationship between AC injection rate and PCDDs/Fs removal efficiency (Kim and Kim, 2004)

Thus, 150~300 mg/Nm^3 AC feeding rate was the optimal feed rate to obtain the minimum dioxins emission for the general SBF system used in MSWI (Kim and Kim, 2004).

Effect of PCDDs/Fs concentration at the inlet of the air pollution control device

Many experimental data indicated that the emissions of PCDDs/Fs at the outlet of BF were not likely guaranteed to be low enough to meet the more stringent emission standard, for instance: 0.1 ng TEQ/Nm^3 in EU, 0.3 ng TEQ/Nm^3 in US (McKay, 2002; Weber *et al*., 2002), provided the inlet concentration of PCDD/Fs is not below the level of 5 ng TEQ/Nm^3. For such cases, further control measures must be applied in order to meet the low PCDDs/Fs emission requirements, for instance: good combustion control to minimize the PCDDs/Fs concentration at the BF inlet. Combustion-related variables affecting the destruction, formation, and furnace emissions include combustion temperatures and residence times, the amount and distribution of combustion air, and mixing (Kilgroe *et al.*, 1990; 1992). Combustion temperatures and residence times of 980 °C and 1~2 s, respectively, are generally believed sufficient to destroy thermally gas-phase compounds. The amount of excess air used for combustion must be sufficiently high to minimize the existence of fuel-rich pockets and sufficiently low to avoid quenching of combustion reactions. Good combustion practices based on state-of-the-art MWCs provide proper air distribution to the combustion bed to complete combustion of pyrolysis products. Methods of achieving good mixing include the use of furnace configuration and overfire air jets.

Effect of particulate concentration

As emission rates of PCDDs/Fs from BF are closely related to the particulates passing through the filter, it is essential to control the particulates emissions to a level as low as possible, i.e. less than 10 mg/Nm^3 (Mätzing *et al.*, 2001).

Effect of BF pressure drop

In an SBF system, pressure drop across the bag increased resulting from the filter cake formed by the activated carbon and fly ash particles. When the pressure was increasing, the PCDDs/Fs and particulates concentration were measured, results are shown in Fig.4. The concentrations of PCDDs/Fs at the BF outlet increased as the BF pressure drop increased, which were correlated with increasing particulates escaping from the BF under the higher pressure drop condition causing emission of PCDDs/Fs adsorbed on the fine particles with average mean diameter of 0.8 μm (Kim and Kim, 2004). The particulates concentration at the outlet is nearly constant up to 1667 Pa, but increases rapidly when higher pressure built up. Thus, less than 1667 Pa of operating pressure drop in the BF should be maintained.

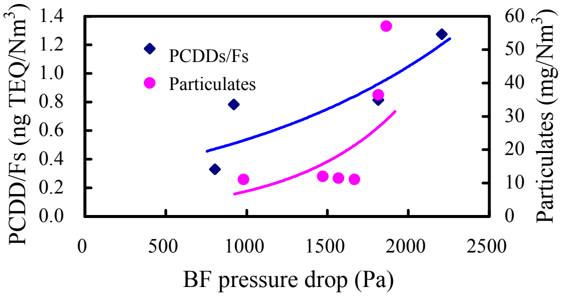


Fig.4 Relationship between PCDDs/Fs emissions and dust concentration vs filter pressure drop

MODELING OF ENTRAINED FLOW ADSORPTION

Global kinetics

The equilibrium adsorption characteristics are represented as Langmuir or Freumdlich isotherms, where the concentration of adsorbed gas on solid is expressed in terms of the equilibrium partial pressure of the adsorbate at constant temperature. Because adsorption is an exothermic process, the concentration of adsorbed gas decreases with increasing temperature at a given equilibrium pressure. The adsorption equilibrium is highly dependent on the solid used and adsorbents with different characteristics resulting in significant differences in adsorption. Some characteristic data on PAC are given in Table 3 (Kim and Kim, 2004) for reference.

Table 3 Characteristics of the activated carbon powder samples (Kim and Kim, 2004)

Characteristics	Value		
	Type S	Type N	Type Y
Surface area (m^2/g)	–	–	–
Single-point BET	678.800	906.300	685.700
Multi-point BET	651.500	885.100	665.600
Langmuir surface area	1380.000	2031.000	1221.000
Meso-pore area	124.900	225.500	80.600
DR-method micro-pore area	982.400	1316.000	999.900
Cumulative ads. surface area	310.500	586.000	426.500
Cumulative des. surface area	319.900	561.300	413.700
Total pore volume (ml/g)	0.513	0.771	0.435
Average pore radius (A^0)	15.800	17.400	13.100
Num. wt. mean (μm)	16.100	11.000	12.400
Vol. wt. mean (μm)	42.500	64.800	52.500
Particle size range (μm)	6~160	4~330	5~230

Adsorption mechanism

Adsorption is the accumulation of molecules on the free surface area of a solid resulting from the saturation of free bonding forces (Everaert *et al.*, 2003). Porous adsorbents are used which are mainly determined by the nature of the adsorbents and by the surface area of the adsorption pores. Some characteristic data on PAC is given in Table 3.

During the entrained flow adsorption, adsorption occurs in the entrained-phase transport at high gas velocities as well as high degree of dispersion in fine-particle cake even at a low velocity in cake filtration. The effective rate of adsorption is determined by the following steps: (1) The mass transfer from the gas phase to the external surface of the adsorbent particles; (2) The mass transfer through pore diffusion within the particles and the adsorption at the phase boundary are usually very fast.

The overall efficiency of the PCDDs/Fs removal (η_{T}) consisted of removal efficiency of solid phase ($\eta_{\text{T-S}}$) and gaseous PCDDs/Fs ($\eta_{\text{T-G}}$). The gaseous PCDDs/Fs, on average a 2~5 fold of the gaseous concentrations of PCDDs/Fs is reported to be associated with fly ash. The PCDDs/Fs originally adsorbed on fly ash and the solid phase PCDDs/Fs can be assumed to remove over in excess of 99.9% by BF. Thus, η_{T} is given by

$$\eta_{\text{T}}=\eta_{\text{T-S}}+\eta_{\text{T-G}}, \tag{1}$$

$$\eta_{\text{T-S}}=\alpha\eta_{\text{dedust}}, \tag{2}$$

where α is fraction of PCDDs/Fs originally adsorbed on fly ash and with solid phase PCDDs/Fs, η_{dedust} is dust removal efficiency of BF.

Adsorption of gaseous PCDD/Fs in entrained flow

Two adsorption processes occur successively, the first is that PAC is homogeneously dissipated into the flue gas and concurrently transported with the gas; the second is entrained flow passes through the filter cake. The adsorption phenomena present in both processes, which facilitates definition of the adsorption efficiency in respective range. The overall removal efficiency of the gaseous PCDDs/Fs is hence a combined effect of adsorption during concurrent transport of flue gas and adsorption in the filter cake, $\eta_{\text{T-G}}$ is given by

$$\eta_{\text{T-G}}=1-(1-\eta_{\text{t}})(1-\eta_{\text{f}}), \tag{3}$$

where η_{t} is removal efficiency of transport process, η_{f} is removal efficiency of filter cake.

For the adsorption in transport and cake filtration, Shin *et al.*(1999) initially advocated a basic model, wherein the effect of previous occupied sites of adsorbing PAC, fly ash and lime in cake filtration were not well considered. Everaeart *et al.*(2003) and Lu (2004) modified the model in this regard (Tables 4 and 5), and presented in Table 4 expressions of specific parameter of A_{a} slightly different from the original model.

Transport (Shin *et al.*, 1999):

$$\eta_{\text{t}}=1-\exp(-k_1A_{\text{a}}t_{\text{f}}), \tag{4}$$

where k_1 is adsorption coefficient in transport (Nm^3/(s·mol)), A_{a} is number of available adsorption sites (mol/Nm^3), T is operating temperature (°C), t_{f} is residence time of adsorbent in transport (s), C_{F} is concentration of fly ash (g/Nm^3), C_{lime} is concentration of injected lime (g/Nm^3), C_{AC} is concentration of

Table 4 Related equations for A_{a}

Equation for A_{a}	Reference
$A_{\text{a}}=\exp(-0.0136T)[1\times10^{-5}(C_{\text{F}}+C_{\text{lime}})+6\times10^{-4}C_{\text{AC}}]$	(Shin *et al.*, 1999)
$A_{\text{a}}=5\times10^{-3}\exp(-0.02T)(C_{\text{AC}}+C_{\text{F}})$	(Everaeart *et al.*, 2003)
$A_{\text{a}}=7.14\times10^{-5}\exp(-0.02T)(0.1S_{\text{AC}}C_{\text{AC}}+C_{\text{F}}+C_{\text{lime}})$	(Lu, 2004)

Table 5 Related equations for η_{f}

Equation for η_{f}	Reference
$\eta_{\text{f}}=1-\exp[k_2A_{\text{a}}/(C_{\text{F}}+C_{\text{lime}}+C_{\text{AC}})v_{\text{f}}]$, k_2=1.5×10^6 g/(mmol·s)	(Shin *et al.*, 1999)
$\eta_{\text{f}}=1-\exp[k_2(\rho_{\text{B}}\times10^3)(f_{\text{A}}+f_{\text{F}}/60)t_{\text{f}}A_{\text{s}}f_{\text{s}}]$, $k_2=k_1\dfrac{v_{\text{f}}}{v_{\text{t}}\varepsilon}, f_{\text{A}}=\dfrac{C_{\text{A}}}{C_{\text{A}}+C_{\text{F}}}, f_{\text{F}}=\dfrac{C_{\text{F}}}{C_{\text{A}}+C_{\text{F}}}$	(Everaeart *et al.*, 2003)
$\eta_{\text{f}}=1-\exp\left(-k_2\dfrac{d\varepsilon^2f_{\text{s}}7.14\times10^{-5}\exp(-0.02T)(0.1S_{\text{AC}}C_{\text{AC}}+C_{\text{F}}+C_{\text{lime}})}{C_{\text{AC}}+C_{\text{F}}+2.2C_{\text{lime}}}\dfrac{1}{v_{\text{f}}}\right)$, k_2=1.5×10^6 g/(mmol·s)	(Lu, 2004)

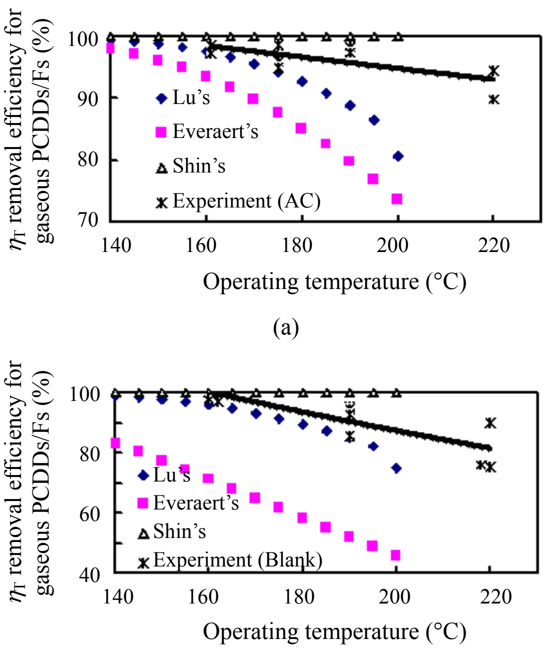
fly ash (g/Nm^3), S_{AC} is surface area determined by multi-point BET (m^2/g). k_1 is derived by fitting the experimental results (Shin *et al.*, 1999) as 9200 Nm^3/(s·mol).

Filter cake, see Table 5, where k_2 is adsorption coefficient in filter cake [Nm^3/(s·mol) or g/(mmol·s)], v_f is Filtration velocity (m/s), ρ_B is bulk density of filter cake (kg/m^3), ε is voidage of the filter cake, d is thickness of filter cake (m), f_s is fraction of unoccupied sites of adsorbent.

Evaluation of the models

Computational results were compared with experimentally measured efficiencies (Kim and Kim, 2004; Tejima *et al.*, 1996). The input parameters for the simulation were selected in accordance with the typical operating conditions: C_F=5.0 g/Nm^3; C_{AC}=0.1 g/Nm^3; C_{lime}=0; t_f=3 s; v_f=0.01 m/s; ε=0.5; v_t=2 m/s; f_s=0.1; d=0.002 m; ρ_B=1010 kg/m^3; S_{AC}=885.1 m^2/g.

Within the possible range of normal operating temperature (140~200 °C), the data obtained from computation using different models are plotted for the conditions with and without AC (Figs.5a and 5b, respectively).



(a)

(b)

Fig.5 Comparison of prediction and measured PCDDs/Fs removal efficiency with AC injection (a) and without AC injection

PCDDs/Fs removal efficiency without AC injection

As can be seen in Figs.5a and 5b, firstly, Lu's prediction results match those with the experimental data in the best conditions; secondly, the similar general trends can be observed in the data calculated by Lu's and Everaert's models, although the latter are considerably lower than the curve drawn from experimental data; lastly, Shin's predictions always tended to overestimate the removal efficiency to higher level. It can be explained by: (1) No consideration of the effect of previous occupied sites of adsorbent surface leads to overestimation of removal efficiency in the filter cake adsorption; (2) Introduction of geometry parameters to describe the filter cake status (Lu's model) produces better prediction results than those without it (Everaert's model).

Figs.5a and 5b show that model predictions proposed by Lu are in reasonable agreement with the measured results under typical operating conditions in the field, thus, the use of the Lu's model enables reasonable prediction of η_T. It can be safely concluded that the model predictions are meaningful and can be applied to predict the removal efficiencies of PCDDs/Fs for combinations of various operating parameters.

DUAL BAG FILTER (DBF) AS AN INNOVATIVE ENTRAINED FLOW ADSORPTION TECHNOLOGY

Introduction of DBF

As the conventional entrained flow adsorption using a single bag filter system can result in excessive activated carbon consumption because of the low utilization efficiency (less than 3%) of carbon. Also, it is difficult to meet the more stringent future emission standard of PCDDs/Fs (0.1 ng TEQ/Nm^3), or even at present it is hard to satisfy the current PCDDs/Fs emission standard (0.5 ng TEQ/Nm^3) if bad combustion occurs. For such problem, Dual Bag Filter (DBF), a modified technology was proposed and tested by Kim and Kim (2004).

DBF system is illustrated in Fig.6. In the first bag filter, fly ash and particle fraction of PCDDs/Fs are intercepted by the bag surfaces and removed by filtration. But gaseous fraction of PCDD/Fs escapes the first bag filter. In the second bag filter of the system, activated carbon is injected in the middle of the entrance duct of the second bag filter, which adsorbs gaseous PCDDs/Fs in the flue gas stream. The discharged activated carbon on the bottom of the second bag filter is re-circulated to mix with the fresh AC and injected into the duct to obtain high utilization efficiency of the carbon.

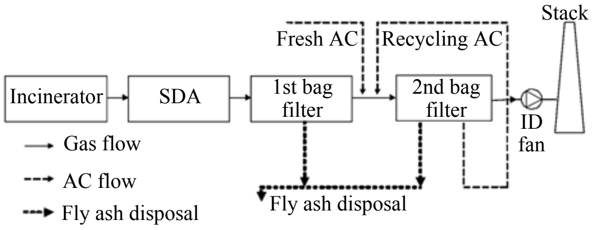


Fig.6 Schematic diagram of DBF system (Kim and Kim, 2004)

Analysis on DBF

Advantages of DBF: (1) Adsorption efficiency of the AC for gaseous PCDD/Fs is greatly increased in the presence of the clean flue gas, which is susceptible to the interference by fine fly ash particulate; (2) Use of the recycled activated carbon reduces the consumption of AC considerably; (3) In DBF, other cheaper materials such as pulverized coke with relatively low surface area, which proved to be effective, can be substituted as the adsorbents; (4) Similar to the adsorption of PCDDs/Fs, it is likely to improve the advantages of using two bag filter will lead to improved removal efficiencies in the emissions of both fine particulates and other heavy metals from MSWI. Heavy metals such as Hg, Cd and Pb are adsorbed or concentrated in the fine particle matters. Filtering the PM emission twice by the dual bag filter will likely reduce both the PM2.5 and heavy metal emission significantly.

Disadvantages of DBF: (1) The capital cost of construction is increased for the second bag filter; (2) the power consumption will slightly increase due to the pressure drop caused by the second Bag filter.

CONCLUSION

The abatement of PCDDs/Fs emissions from MSWI can be achieved by the available techniques, such as the process-integrated entrained-flow injection of powdered adsorbents in the flue gas followed by baghouse filter separation, and the fixed/moving bed adsorbers. This work focuses on the former technique.

The influencing factors such as flue gas temperature, feeding rate of AC, PCDDs/Fs concentration at the inlet of the APCD, pressure drop across the filter on PCDD/Fs removal efficiency are reviewed, showing that: (1) The removal efficiency without the injection of activated carbon correlates closely to flue gas temperature; increases with decrease of temperature; (2) When the flue gas temperature at the BF inlet is maintained at 160~190 °C, the injection of AC at 150 to 300 mg/Nm^3 injection rate into the duct achieves a removal efficiency of 95%~98%. PCDDs/Fs concentrations at the BF inlet must be maintain below 5 ng TEQ/Nm^3, the other operational parameters are applied according to those optimal conditions discussed above, then the PCDDs/Fs concentration at the FF outlet can be maintained below the 0.1 ng TEQ/Nm^3 with very good marginal capacity; (3) Whereas in regard to the filter material, it is essential to control the particulates concentration as low as possible, i.e. lower than 10 mg/Nm^3 at BF outlet; (4) The emissions of PCDDs/Fs at the BF outlet increased with increased BF pressure drop, and operating pressure drop in BF below 1667 Pa should be maintained.

Evaluation of various mechanistic models for entrained-flow adsorption was carried out based on the computational simulation applying actual operating conditions and theoretical analysis. Good predictive results were obtained through using Lu's model enables the prediction of η_T with higher precision. It can be safely concluded that the model predictions are meaningful and can be applied to predict the removal efficiencies of PCDDs/Fs under various combinations of operating parameters.

Finally, enhancement of entrained-flow adsorption by the application of dual bag filter is analyzed. It appears that combined entrained-flow adsorption and dual bag filter have high potential to be a multi-pollutant technology for decreasing the emissions of PCDDs/Fs, mercury and other heavy metals and fine particulates from MSWI. Researches for measuring the control efficiencies for Hg and other heavy metals, fine PM of the combined entrained-flow adsorption with dual bag filter technology will be conducted in future.

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