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Determining optimal operation parameters for reducing PCDD/F emissions (I-TEQ values) from the iron ore sintering process by using the Taguchi experimental design

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Abstract

This study is the first one using the Taguchi experimental design to identify the optimal operating condition for reducing polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs) formations during the iron ore sintering process. Four operating parameters, including the water content (Wc; range = 6.0–7.0 wt %), suction pressure (Ps; range = 1000−1400 mmH_2O), bed height (Hb; range = 500−600 mm) and type of hearth layer (including sinter, hematite, and limonite), were selected for conducting experiments in a pilot scale sinter pot to simulate various sintering operating conditions of a real scale sinter plant. We found that the resultant optimal combination (Wc=6.5 wt%, Hb=500 mm, Ps=1000 mmH_2O, and hearth layer= hematite) could decrease the emission factor of total PCDD/Fs (total $EF_{PCDD/Fs}$) up to 62.8% by reference to the current operating condition of the real-scale sinter plant (Wc=6.5 wt %, Hb = 550 mm, Ps = 1200 mmH_2O, and hearth layer = sinter). Through the ANOVA analysis, we found that Wc was the most significant parameter in determining total $EF_{PCDD/Fs}$ (accounting for 74.7% of the total contribution of the four selected parameters). The resultant optimal combination could also enhance slightly in both sinter productivity and sinter strength (30.3 t/m^2/day and 72.4%, respectively) by reference to those obtained from the reference operating condition (29.9 t/m^2/day and 72.2%, respectively). The above results further ensure the applicability of the obtained optimal combination for the real-scale sinter production without interfering its sinter productivity and sinter strength.

Keywords: PCDD/F formation, iron ore sintering, Taguchi experimental design, optimization, operation parameter

Running Title: Optimizing operating parameters for reducing PCDD/F emissions by using the Taguchi experimental design

Outline of Section Headers

Introduction

Material and Methods

Results and Discussion

Literature cited

Introduction

Iron ore sintering is an agglomeration process to convert iron ore fines (raw mixture) into lumpy agglomerates. In the preliminary stage of sinter making process, water was sprayed onto the raw mixtures in the mixing drum to increase the granular sizes for enhancing the permeability of the sinter bed. During sintering, the raw mixtures were first ignited by gas-fueled (nature gas) burns situated at the beginning of the steel belt conveyer. Then, the sinter bed was heated to temperature ~1000 ºC or above. Suction air passes through the sinter layer by means of wind legs and a fan, which moves the melting/combustion zone to the down layer to produce sintered products.

Mechanisms associated with the formations of dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs) in the sintering process are very complicated. Possible formation mechanisms might be related to precursor reactions (*1-2*) and combustion conditions of sinter raw mixtures (*3-5*). Particiularly, PCDD/Fs could also be formed through de novo synthesis reaction in the dry zone of the sinter bed under various combustion conditions (*2, 6*). Many studies have indicated that the four operating parameters, including the water content (Wc) (*7*), suction pressure (Ps) (*8*), bed height (Hb) (*9*) and type of the hearth layer (*10*), are major factors affecting combustion conditions during the iron ore sintering process. Among these four parameters, the content of Wc in the sinter zone might affect the adsorption of PCDD/Fs on the surface of particles and the solubility of PCDD/Fs in water (*7*); the magnitude of Ps affects the air (or oxygen) supply which might play an important role in the oxygen-chlorine interactions related to PCDD/Fs formation (*8*); Hb affect the thickness and temperature profile of the combustion zone of the sinter bed and in consequence affects the contents of unburned hydrocarbon compounds during the sintering process (*9*); and the type of the hearth layer might affect the catalytic oxidation reaction associated with PCDD/F formations (*10*). All these operating parameters have been used to control the structure of the sinter bed to simulate various operation conditions for the sintering process in many studies (*11-14*).

Since the discovery of PCDD/Fs from the fly ash of a municipal solid waste incinerator (MSWI) (*15*), PCDD/F emissions from various emission sources, such as MSWI, power generation, metallurgical process and chemical-industrial sources has became a significant environmental issue (*16*). Among them, PCDD/F emissions from iron ore sinter plants have been recognized as the most important source in many countries (*17-19*). To date, most sinter plants have installed various air pollution control devices (APCDs) for the control of PCDD/F emissions. Nevertheless, most sinter plants have faced the dilemma regarding how to continuously upgrade their APCDs in order to comply with stricter and stricter emission standards adopted in their countries. In order to comply with future PCDD/F emission standard and decrease the cost resulting from upgrading the end-pipe PCDD/F control devices, it is important to develop an effective method for directly reducing PCDD/F generations during the sintering process. It is known that the change of the contents of sinter raw mixture for reducing PCDD/F emissions would be impractical in the real situation. Therefore, to optimize operating conditions in order to reduce PCDD/F formations via de novo synthesis reaction in the dry zone of the sinter bed might provide a promising solution.

In principle, experimental design methods can be used to determine the optimal operating condition for a given purpose. For many years, experimental design methods originally developed by Fisher have been widely used in many industries (*20*). However, the use of the above methods might be subjected to their complexities and their requirement for a large number of experiments to be carried out as the number of the designed parameters increased. To solve the above problems, the Taguchi experimental design is considered as a less complicated method requiring only much smaller number of experiments to be conducted for identifying an optimal operation condition. The Taguchi experiment design is a powerful tool that provides a simple, efficient and systematic approach to optimize operating conditions under designated ranges of all selected parameters. The method is valuable when the designed parameters are qualitative and discrete. The method can used to optimize the performance characteristics through the settings of designed parameters and reduce the sensitivity of the system performance to sources of variation. In recent years, the Taguchi experiment design has been used in many industries to optimize the operating conditions for the waste water treatment and air pollution control (*21-24*). Therefore, in the current study the Taguchi experimental design is used to determine the optimal operating combination for reducing PCDD/F formations during the sintering process. In addition, two important indexes (i.e., the sinter productivity and sinter strength) widely used for characterizing the quality of the sintering products were also examined to further ensure the optimal combination obtained from the Taguchi experiment design can be used in the real scale sinter plant.

Material and Methods

The Pilot Scale Sinter Pot and Its Operating Procedures. A pilot scale sinter pot was used in this study to simulate the real-scale sintering process (Fig. 1). This sinter pot included a pot body (inner diameter = 330 mm, height = 600 mm), an ignition hood, and a windbox connected to an exhaust duct. Six kilogram of hearth layer (particle diameters = 10–15 mm, thickness = 40 mm) were placed inside the sinter pot. During sintering, the designated ignition temperature in ignition hood was specified at 1150–1200 ℃ for 1.5 minutes and then hold in another 1.5 minutes for keeping heat. During this period (i.e., starting from the ignition to the removal of the ignition hood) the suction pressure inside the sinter pot was controlled at 800 mmH_2O by using an electromagnetic valve. After this, the suction pressure was raised to 1200 mmH_2O and then kept constant throughout the end of the sintering process. The total sintering time was around 35 minutes depending on the experimental conditions.

The sintering raw mixture used in this study was directly obtained from the real-scale sinter plant. It consisted of the iron ore (52.8 wt %), coke breeze (4.0 wt %), anthracite (1.84 wt %), serpentine (0.42 wt %), marble (1.98 wt %), slurry (0.56 wt %), and return fine (31.5 wt %; including return fine obtained from sinter plant and blast furnace), and mini-pellet (1.50 wt %) with mean granular sizes ranging from 1.0 to 6.3 mm. The sintering raw mixture was found with 5.81% FeO, 9.38% CaO, 1.44% MgO, 1.66% Al_2O_3, 4.79% SiO_2, and total-Fe accounting for 57.5% total weight..

Taguchi Experimental Design. The working steps for the Taguchi experimental design include: (1) selection of operation parameters; (2) determination of the number of levels for each selected parameter; (3) selection of the appropriate orthogonal array and arrangement of operation parameters to the orthogonal array; (4) conducting experiments based on the arrangement of the orthogonal array; (5)

analysis of the experimental results using the S/N ratio and ANOVA analyses; (6) selection of the optimal combination of levels for the selected operation parameter; and (7) verification of the above optimal combination by conducting a confirmation experiment (*25,26*).

Selected Operation Parameters, levels and Orthogonal Array. Four operation parameters (and their testing ranges), including water content (Wc; 6.0–7.0 wt %), suction pressure (Ps; 1000–1400 mm H_2O), bed height (Hb; 500–600 mm), and types of hearth layer (including sinter (containing 70% Fe_2O_3 and 7% Fe_3O_4; Fe in total accounting for 58.1% of total weight), hematite (containing 88% Fe_2O_3 and 7% FeO·OH; Fe in total accounting for 64.1% of total weight), and limonite (containing 40% Fe_2O_3, 45% FeO·OH and 6% H_2O; Fe in total accounting for 63.3% of total weight)) were selected in this study. The selected ranges of the above four parameters were determined based on the past operation experience of the selected sinter plant and the published references (*11, 27-28*). A specific combination of the four selected operation parameters (i.e., Wc = 6.5 wt %, Ps = 1200 mmH_2O, Hb = 550 mm, and type of hearth layer = sinter) being currently used in the real-scale sinter plant was served as the reference combination. Table 1 shows the selected three levels for each operation parameter based on its designated range. An $L9(3^4)$ orthogonal array (with four columns and nine rows) was used in this study according to the Taguchi experimental design (Table 2) (*25*). Since the experimental design was orthogonal, it was possible to discriminate the effect of each individual parameter at each designated level. As shown in Table 2, nine combinations of the four selected operation parameters were chosen for conducting experiments. Subjected to the cost associated with PCDD/Fs samplings and sample analyses, each experiment were repeated twice (n=2) in this study.

PCDD/Fs sampling. For each experiment, the flue gas samples were collected from the duct located at the downstream of the windbox of the pilot sinter pot (see Fig 1) by using a Graseby Anderson stack isokinetic sampling system (compliance with US EPA Method 23). The sampling location was in accordance with the stack sampling criteria (i.e., in 8 times distance of duct diameter (8D) away from downstream of the curvature) and in 2 times distance of duct diameter (2D) away from upstream of the curvature) for preventing uncertainty caused by flow turbulence. Because the instability of the airstream occurred during the first five minutes of the sintering process (i.e., the time needed for adjusting the suction pressure to reach the designated level), the flue gas of the first five minute was not collected. As a result, the sampling time for each flue gas sample was ~30 minutes.

PCDD/Fs analysis. Analysis of PCDD/Fs for all collected samples followed the US EPA modified Method 23 by an accredited lab in the Super Micro Mass Research and Technology Center of the Cheng-Shiu University. Each collected sample was first spiked with a known amount of the internal standard. Seventeen PCDD/F congeners in gas- and particle- phase were analyzed, respectively. For each collected sample, it was first extracted for 24 h, then the extract was concentrated, treated with concentrated sulfuric acid, and then followed by a series of sample cleanup and fractionation procedures. The eluate was concentrated to 1 mL, then transferred to a vial, and then further concentrated to nearly dryness by using a nitrogen stream. PCDD/Fs were analyzed by a high-resolution gas chromatography (HP 6970) / high-resolution mass spectrometry (HRGC/HRMS) with a DB-5 capillary column (60 m × 0.25 mm i.d., 0.25 μm film thickness; J&W Scientific, CA, USA). Injections were made in splitless mode with a column oven temperature program of 150 ℃, 30 ℃/min to 220 ℃ (5 min), 1.5 ℃/min to 240 ℃ (5 min), than 15 ℃ /min to 310 ℃ (20 min). Injector and detector temperature were 250 ℃ and 310 ℃, respectively. Helium was used as carrier gas (1.2 mL/min). The HRMS (Micromass Autospec Ultimate) was equipped with a positive electron impact (EI+) source as 35ev electron energy and ionization temperature at 250 ℃. The analyzer mode of the selected ion monitoring (SIM) was used with resolving power at 10,000.

Analysis of the serial dilution of PCDD/F standards showed that the method detection limits (MDL) of HRGC/HRMS was 0.127-2.27 pg. PCDD/F recovery efficiencies were determined by processing a solution containing with known PCDD/F concentrations through the same experimental procedure used for the samples. The recovery efficiency of PCDD/Fs varied between 74.3 % and 96.1 % and averaged 84.8% in this study. The mean relative standard deviation (RSD) (%) of recovery efficiencies was 18.6% (range 15.1–22.8%). The blank tests for PCDD/Fs were accomplished by the same procedure as the recovery-efficiency tests without adding the known standard solution before extraction. Analysis of blanks showed no significant contamination.

Concentrations of PCDDs, PCDFs, gas- and particle-phase PCDD/Fs, and total PCDD/Fs of flue gas samples obtained from the nine selected experimental combinations were calculated. Because the purpose of the present study was aimed at reducing the environmental impact arising from PCDD/F emissions, therefore the I-TEQ concentration (i.e., ng I-TEQ/Nm^3) was used to characterize the above concentrations. Considering the variations in flow rate, sintering time, and charging weight of feedstock among different experimental combinations, the emission factor of PCDD/Fs ($EF_{PCDD/Fs}$; ng I-TEQ/kg-feedstock) were calculated for comparisons.

Evaluation of sinter productivity and sinter strength. The sinter productivity, expressed in tons per square meter of grate area of sintering machine per day, was calculated from the sintering time, the cross-sectional area of the pot grate, and the weight of sinter product recovered from the test (by removing the loss of the weight of hearth layer). The sinter strength was measured by using a modified ISO 3271 test method (*29*).

Data analysis. The S/N ratio based on the concept of the-lower-the-better was used to characterize $EF_{PCDD/Fs}$. The S/N ratio (η) was defined as (*25*):

$$\eta = -10\log(\text{M.S.D.}) \quad (1)$$

Where, mean-square deviation (M.S.D.) was the calculated variance for the characteristic value *y*. The S/N ratio in decibel (dB) units was used due to the value of ten times the common log of equation (Eqs. 1) for comparison. The M.S.D. characterized the-lower-the-better was obtained as:

$$\text{M.S.D.} = \frac{1}{n}\sum_{i=1}^{n} y_i^2 \quad (2)$$

Where, n was number of test, and y_i was the value of $EF_{PCDD/Fs}$ obtained from the ith test. The predicted S/N ratio (or $EF_{PCDD/Fs}$) (β) for the optimal combination could be calculated as:

$$\beta = \eta_m + \sum_{i=1}^{o}\left(\overline{\eta}_i - \eta_m\right) \quad (3)$$

Where, η_m was the total mean S/N ratio, $\bar{\eta}_i$ was the maximum S/N ratio (or the minimum $EF_{PCDD/Fs}$) obtained from the *i*th parameters in their three designated levels, and *o* was the number of our selected parameters.

In addition, the analysis of variance (ANOVA) was used to investigate the effect of each individual parameter on $EF_{PCDD/Fs}$.

Results and Discussion

Concentrations and characteristics of PCDD/Fs emitted from the sinter process. Table 3 shows concentrations of PCDDs, PCDFs, gas- and particle-phase PCDD/Fs, and total PCDD/Fs of flue gas samples obtained from the nine selected experimental combinations. The mean total PCDD/F concentration was 0.940 ng I-TEQ/Nm^3 (range = 0.279−1.70 ng I-TEQ/Nm^3), which was mostly contributed by gas-phase PCDD/Fs (in average accounting for 63% of total PCDD/Fs). These levels were similar to those reported by Wang et al. (*30*), and Anderson and Fisher (*18*). PCDFs had a higher fraction (53.5−83.8 %) in total PCDD/Fs in all experimental combinations than that of PCDDs (16.2−46.5 %). Considering intrinsic differences in flow rate, sintering time and charging weight among the nine selected experimental combinations, Table 3 also shows the total PCDD/F emission factor (total $EF_{PCDD/Fs}$) for each combination. We found that the mean total $EF_{PCDD/Fs}$ for the nine selected experimental combinations was 5.16 ng I-TEQ/kg-feedstock (range = 1.01−9.37 ng I-TEQ/kg-feedstock). However, it should be noted that the trend in magnitude of total $EF_{PCDD/Fs}$ was somewhat different from that of total PCDD/F concentrations for the nine selected experimental combinations. The above result clearly indicates the importance of using total $EF_{PCDD/Fs}$ to determine the optimal combination for reducing PCDD/F emissions from the sintering process.

Figure 2 showed the congener profiles of the 2,3,7,8-substituted PCDD/Fs (mean and range) of the nine selected experimental combinations. The most abundant congeners collected from the sinter pot, presented in sequence, were 2,3,7,8-TeCDF, 2,3,4,7,8-PeCDF, 1,2,3,4,6,7,8-HxCDF, 1,2,3,7,8-PeCDF, and OCDD. The above results were similar to those presented in other studies (*18, 30*).

S/N ratios and ANOVA analysis. In this study, the total $EF_{PCDD/Fs}$ obtained from the nine selected experimental combinations were used to calculate S/N ratio. The S/N ratios of the four selected parameters in three designated levels according to the orthogonal array experimental arrangement were presented in Table 4. We found that the resultant S/N ratios fell to the range from -0.69 to -19.6 dB. Table 5 shows mean S/N ratios of the four selected parameters in each of their three designated levels. For each selected parameter, the difference between maximum S/N ratio and its corresponding minimum S/N ratio (i.e., max-min) represents the effect of the given parameter on determining total $EF_{PCDD/Fs}$. Based on this, we found that the effects in sequence for the four selected parameters on total $EF_{PCDD/Fs}$ were: Wc (12.3 dB), Ps (4.15 dB), hearth layer (3.45 dB) and Hb (3.15 dB). Figure 3 shows the trend of the resultant S/N ratios for each selected parameters at the three designated levels affecting total $EF_{PCDD/Fs}$. Both Ps and Hb shared the same trend in their resultant S/N ratios (i.e., first decreased then increased). The above trend was different from that of Wc (i.e., first increased then decreased) and hearth layer. The combination of Wc (=6.50 wt %), Ps (=1000 mmHg), Hb (=500 mm), and hearth layer (=hematite) were found with the highest S/N ratio for each of the four selected parameters, and hence was considered as the optimal operation condition for reducing PCDD/F emissions.

In this study, the ANOVA analysis was used to prioritize to effects of the four selected parameters on determining total $EF_{PCDD/Fs}$. Result shows that Wc ($p<0.01$) was the most significant parameter accounting for 74.7% of the total contribution of the four selected parameters (Table 6). The above result was consistent with that found in Suzuki et al. (*4*) and Li et al. (*31*). Here, it should be noted that the optimal Wc was found at the middle level (i.e., 6.5 wt %) might be worth further discussion. Kasai et al. (*32*) and Haga et al. (*33*) have indicated that the increase of Wc in sinter raw mixtures could increase the permeability of sintering bed and combustion efficiency (due to the abundant coke breezes and limestone fines coating on the surface of particles), and hence results in reducing PCDD/F formation during sintering processes. On the other hand, two other studies have indicated that the increase of Wc might lead to the increase of PCDD/F emissions because the adsorption of PCDD/Fs on the surface area of sinter raw mixtures was partly replaced by the water molecules (*4, 31*). Based on these, it is not so surprising to see that the lowest total $EF_{PCDD/Fs}$ was found at the middle level (i.e., 6.5 wt %) rather than at 6.0 wt % or 7.0 wt %. The optimal Ps and Hb were found at their corresponding lowest levels (1000 mmH_2O and 500 mm, respectively). The above results might because the lower Ps and Hb might result in a wider combustion/melting zone in the sinter bed, leading to a more complete coke combustion and less PCDD/F formation during the sintering process. For the type of hearth layer, we found that the use of hematite could slightly decrease total $EF_{PCDD/Fs}$ in comparison with the use of sinter as the hearth layer of the sinter pot, although the above effect was not significance (p=0.187). Studies have reported that Fe_2O_3 did play an important role in catalytic oxidation of carbon monoxide and polyethylene (*34-35*). The higher Fe_2O_3 content might result in the less PCDD/F formation. The above inference is consistence with what we found in the three selected types of hearth layer in their Fe_2O_3 contents (i.e., hematite (88%) > sinter (70%) > limonite (40%)). The insignificant effect associated with the types of hearth layer used in this study deserves further discussion. It might mainly because the depth of the hearth layer was too thin to have sufficient reaction time for the formation of PCDD/Fs during sintering process. However, it should be noted that other physical parameters of hearth layer, such as the particle size and porosity, could also be important factors affecting PCDD/F formations. Considering the combined effect of all these physical factors on PCDD/F formations were too complicated, which warrants the needs for further research in the future.

Comparison PCDD/F emissions between the reference and the optimal operation combination. Table 7 shows total $EF_{PCDD/Fs}$ and S/N ratios obtained from the reference combination (i.e, Wc=6.5 wt %, Ps=1200 mmH_2O, Hb=550 mm, and hearth layer = sinter) and the resultant optimal combination (i.e., Wc=6.50 w%, Ps=1000 mmHg, Hb=500 mm, and hearth layer=hematite). The total $EF_{PCDD/Fs}$ and its corresponding S/N ratio for the reference combination were found as 3.09 ng I-TEQ/kg-feedstock and -10.8 dB, respectively. For the optimal combination, its total $EF_{PCDD/Fs}$ and S/N ratio (predicted based on Eqs. 3) were found as 1.01 ng I-TEQ/kg-feedstock and -0.694 dB, respectively. The difference in the above two S/N ratios (= 10.1 dB) indicating that the use of the optimal combination would result in a decrease in total $EF_{PCDD/Fs}$ up to 67.3% in comparison with the reference combination. For confirmation purpose, experiments were conducted based on the specification of the resultant optimal combination. The resultant total $EF_{PCDD/Fs}$ and its corresponding S/N ratio were found as 1.15 ng I-TEQ/kg-feedstock and -1.21 dB, respectively. The increase in S/N ratio from the reference combination to the optimal combination (confirmation experiment) was 9.59 dB, and the resultant decrease in total $EF_{PCDD/Fs}$ was up to 62.8%. The above results further confirm the applicability of the obtained optimal combination for reducing PCDD/F formations during the sintering process.

Sinter productivity and sinter strength of the reference and optimal operation combination. Although the resultant optimal combination was able to reduce PCDD/F emissions, it is important to examine its impact on the sinter productivity and sinter strength for practical reason. In this study, we found that the sinter productivity and sinter strength for the reference combination were 29.9 t/m^2/day and 72.2%, respectively. The above values were slightly lower than that of the optimal combination (30.3 t/m^2/day and 72.4%, respectively). Therefore, it is concluded that the use of the optimal combination for the sintering process could effectively reduce PCDD/F emissions without interfering with both the quality and quantity of its sinter products.

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List of Figures

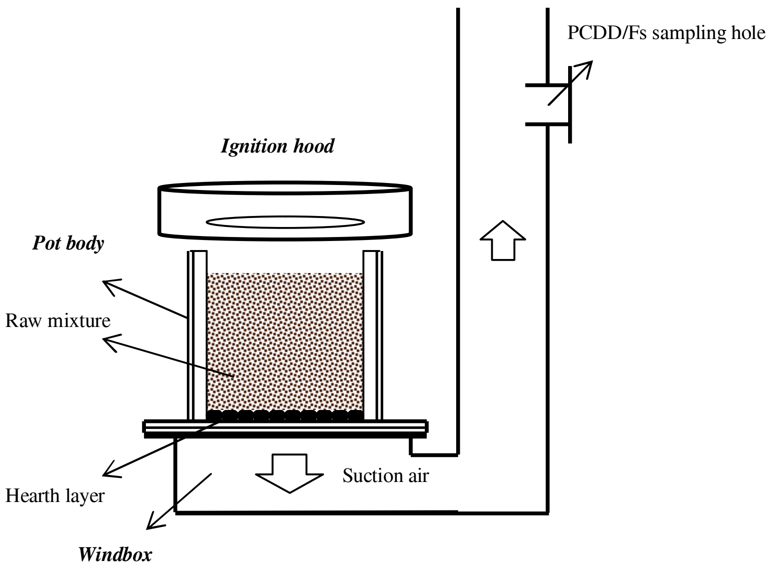

FIGURE 1. The schematic of the pilot scale sinter pot

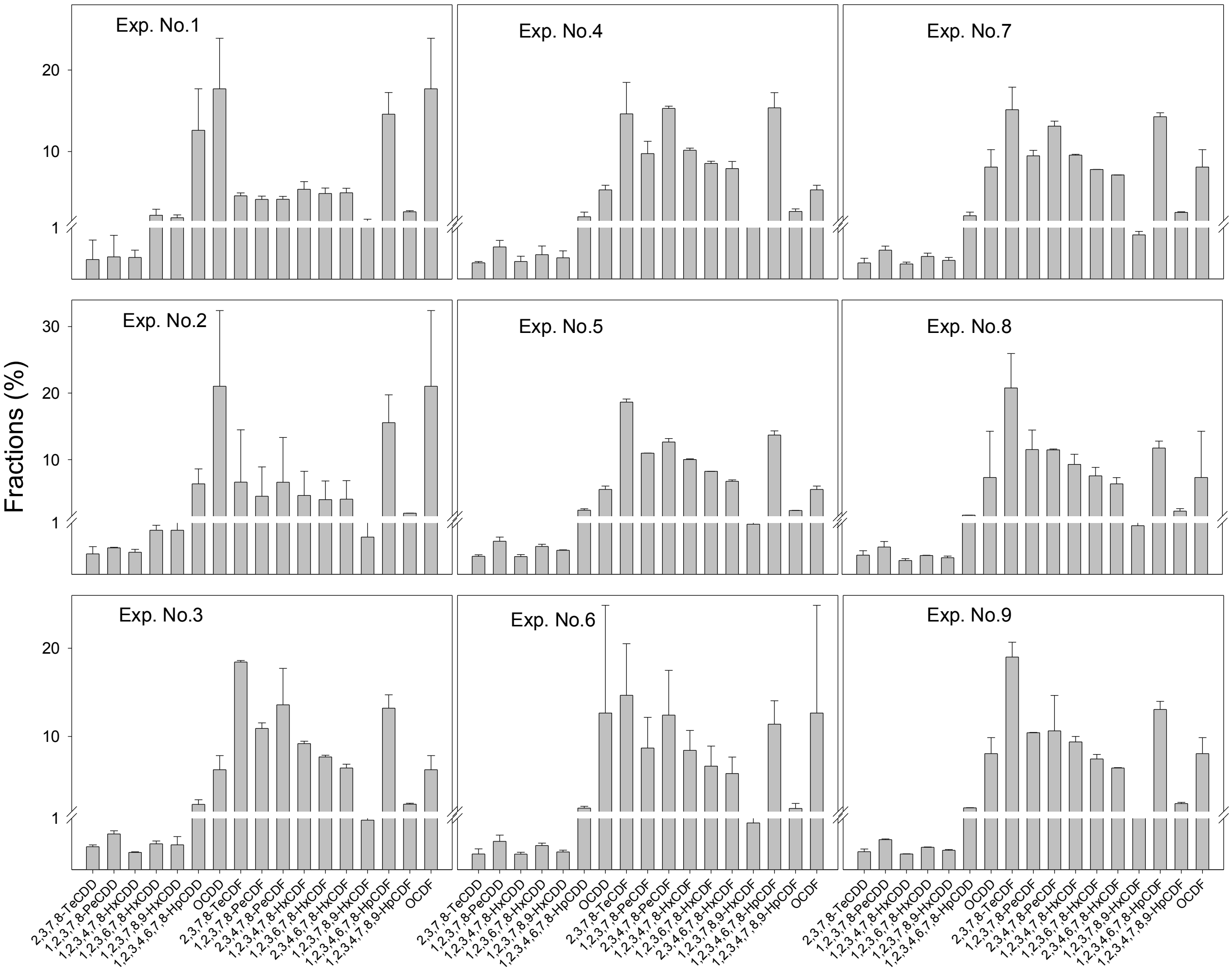

FIGURE 2. Congener profiles of seventeen PCDD/F congeners in the flue gases of sinter pot operated under the nine experimental combinations

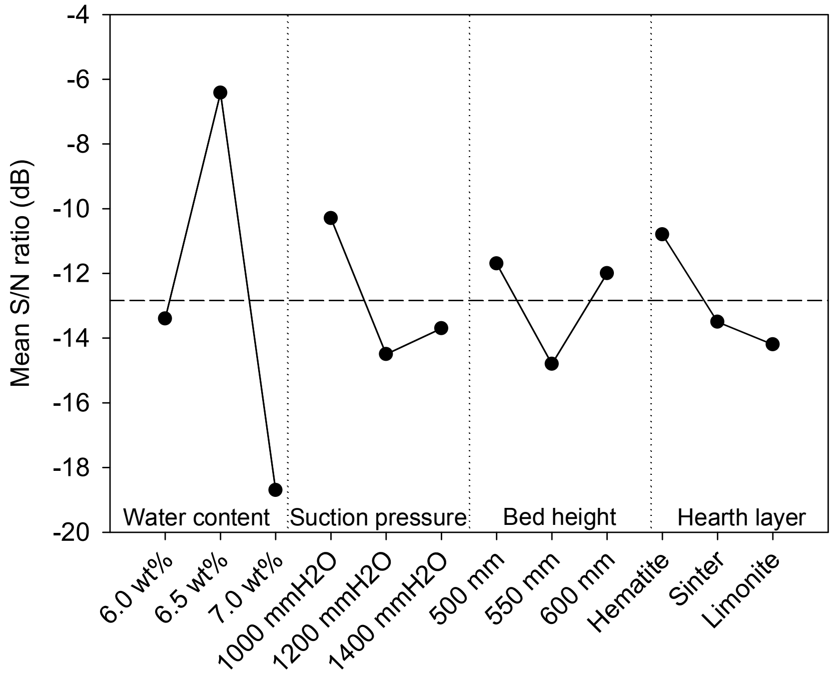

FIGURE 3. Mean S/N ratios of the four selected operation parameters at the three designated levels

List of Tables

Table 1. Operating parameters and their selected levels for the studied sintering process

Operation parameter	Unit	Level 1[a]	Level 2	Level 3
Water content (Wc)	wt %	6.5	6.0	7.0
Suction pressure (Ps)	mmH_2O	1200	1000	1400
Bed Height (Hb)	mm	550	500	600
Hearth layer	-	Sinter	Hematite	Limonite

[a]: Reference combination

Table 2. The nine designed experiment combinations of the four selected parameters for the Taguchi L_9 orthogonal array

Experiment combination	Water content	Suction pressure	Bed Height	Hearth layer
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 3. PCDDs, PCDFs, gas- and particle-phase PCDD/Fs, and total PCDD/Fs emission concentrations (ng I-TEQ/Nm^3) in the flue gas of the nine designed experimental combinations and their corresponding emission factors of total PCDD/Fs ($EF_{PCDD/Fs}$; ng I-TEQ/kg-feedstock)

Emission concentration	Experimental combination								
	1	2	3	4	5	6	7	8	9
PCDDs	0.187	0.040	0.043	0.059	0.049	0.079	0.055	0.075	0.119
PCDFs	0.719	0.238	0.529	0.952	0.666	1.15	0.846	1.08	1.58
Gas-phase PCDD/Fs	0.564	0.196	0.365	0.518	0.325	0.752	0.570	0.963	1.21
Particle-phase PCDD/Fs	0.342	0.082	0.206	0.492	0.390	0.477	0.331	0.191	0.485
Total PCDD/Fs	0.906	0.279	0.571	1.01	0.715	1.23	0.901	1.15	1.70
Emission factor									
Total $EF_{PCDD/Fs}$	3.09	1.01	2.44	5.80	3.45	5.05	7.40	9.37	8.79

Table 4. The resultant S/N ratios for the nine experiment combinations of the Taguchi L_9 orthogonal array

Experiment combination	Water content (%)	Suction pressure (mmH_2O)	Bed height (mm)	Hearth layer	S/N ratio (dB)
1	6.5	1200	550	sinter	-10.8
2	6.5	1000	500	hematite	-0.69
3	6.5	1400	600	limonite	-7.77
4	6	1200	500	limonite	-15.3
5	6	1000	600	sinter	-10.7
6	6	1400	550	hematite	-14.1
7	7	1200	600	hematite	-17.4
8	7	1000	550	limonite	-19.6
9	7	1400	500	sinter	-19.1

Table 5. Mean S/N ratios for the four selected operation parameters in three designated levels

Operation parameter	Mean S/N ratio (dB)				
	Level 1	Level 2	Level 3	Max−Min	Rank
Water content (Wc)	-6.42	-13.4	-18.7	12.3	1
Suction pressure (Ps)	-14.5	-10.3	-13.7	4.15	2
Bed Height (Hb)	-14.8	-11.7	-12.0	3.15	4
Hearth layer	-13.5	-10.8	-14.2	3.45	3

Table 6. Results of the analysis of variance for the four selected parameters

Operation parameter	DOF[a]	SS[b]	Var[c]	F^{d}	p-value	Contribution (%)
Water content (Wc)	2	456	228	22.9	<0.001	74.7
Suction pressure (Ps)	2	58.0	29.0	2.92	0.105	9.49
Bed Height (Hb)	2	36.4	18.2	1.83	0.215	5.95
Hearth layer	2	40.3	20.1	2.03	0.187	6.59
Error	9	89.4	9.93	-	-	3.25
Total	17	680	305	-	-	100

[a]Degree of freedom; [b]Sum of squares; [c]Mean square; [d]F-test

Table 7. The emitted total $EF_{PCDD/Fs}$ concentration and its corresponding S/N ratio obtained from the reference operation combination and optimal operation combination (including both predicted and that obtained from the confirmation experiments).

Testing results	Reference operation combination	Optimal operation combination	
		Prediction	Confirmation
Total $EF_{PCDD/Fs}$ (ng I-TEQ/kg-feedstock)	3.09	1.01	1.15
S/N ratio (dB)	-10.8	-0.694	-1.21