Journal of Hazardous Materials B101 (2003) 273–283

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Co-firing of paper sludge with high-calorific industrial wastes in a pilot-scale nozzle-grate incinerator

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Received 15 January 2003; received in revised form 14 April 2003; accepted 22 April 2003

Abstract

Experiments on the co-firing of high-calorific industrial wastes with paper sludge were performed in a pilot-scale industrial waste incinerator with a nozzle-type grate system. The incineration capacity was approximately 160 kg/h. The temporal variations in the temperatures and exhaust gas emissions were monitored and used as parameters for determining the desirable incineration conditions. The high CO emissions that were mainly due to the rapid vaporization of combustibles from high-calorific industrial wastes could be alleviated through the co-firing of sludge with the high-calorific industrial wastes. Because of the high nitrogen content in the sludge, the increase in the co-firing rate caused higher NO emissions in the flue gas. If the total calorific value of the feed was lower than 750,000 kcal/h, for 25–30% of sludge co-firing, the temperature of gases exiting the secondary combustion chamber might be lower than that required by regulations.

Keywords: Co-firing; Industrial waste; Paper sludge; Nozzle-grate; Incinerator

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1. Introduction

Wastewaters may contain inorganic and toxic components, which on treatment can form sludge. Currently used methods for the disposal of sludge include recycling as a fertilizer, landfilling, dumping at sea, and incineration. With disposal by landfilling, agricultural recycling and disposal to sea facing bans, there is a growing interest in incineration and other thermal sludge disposal processes [1].

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doi:10.1016/S0304-3894(03)00144-4

However, sludge incineration is a potential source of toxic pollutants, such as heavy metals in gaseous emissions as well as dioxins and furans, NO_x, N_2O, SO_x, HCl, HF and hydrocarbons. Additionally, the high ash content of sludge can lead to high ash concentrations in the flue gases.

Korean emission regulation for incineration limits the concentrations of CO, NO_x and SO_x to a maximum of 600, 200 and 300 ppm (at 12% O_2), respectively. Moreover, the temperature of gases exiting from the combustion chamber should be greater than 800 °C, whereas the loss-on-ignition (LOI) of the bottom ash must be lower than 3 wt.% [2].

Because of the low-calorific value and high moisture content of paper sludge, its incineration requires the use of an auxiliary fuel, thereby increasing the operating costs to at least twice that of other disposal methods, such as landfilling or dumping in the sea. Conversely, due to the rapidly volatilized combustible gases, poor mixing of these gases with air and high CO emissions are the most troublesome problem in burning high-calorific industrial wastes, such as plastics and synthetic leather. Therefore, co-firing of industrial wastes with sludge may be an alternative to disposal by other means. Furthermore, most incinerators if equipped with modern flue gas cleaning technology, can be used for the co-firing of sludge with industrial wastes [1].

Typically, for grate firing, the heat released by burning industrial wastes is used to produce steam. This steam can then be utilized for thermal conditioning and/or drying of the sludge. This predrying increases the heating values of the sludge by increasing the combustible solid contents to 55–65% [1].

Seo et al. [3] monitored the emissions of an industrial waste incinerator used to burn plastics with controlled air. They showed that the steep increase of CO emissions in the flue gas was due to unstable combustion in the incipient step of burning. They also reported excessively high CO emissions in the early stage of plastic wastes combustion, and the desirable CO level during the remaining period, in a semi-carbonization two-stage combustor [4]. Jung et al. [5] investigated the effect of oxygen enrichment in a rotary kiln-type incinerator used for the combustion of waste rubber. In these studies, the rapid volatilization of high-calorific wastes and their incomplete mixing with air could explain the excessive CO emissions. The co-firing of high-moisture wastes, like sludge, with industrial wastes could be a good solution to the high CO emissions, by alleviating the rapid volatilization. Werther and Ogada [1] reviewed the formation, treatment, disposal, thermal processes and emissions from co-firing of sewage sludge with municipal solid wastes (MSW). In the case of MSW, about a 10% co-incineration of the sludge was generally recommended. Meanwhile, Tsai et al. [6] conducted co-firing of coal and paper mill sludge in a circulating fluidized bed boiler to investigate the effect of the sludge feed rate on emissions of SO_x, NO_x, and CO. Corella and Toledo [7] studied on incineration of sewage sludge doped with several heavy metals in a small pilot plant scale fluidized bed. In 2003, Neyens and Baeyens [8] reviewed the pretreatment processes of sludge to improve dewaterability.

The purpose of our study was to investigate the co-incineration of sludge with high-calorific industrial wastes, and understand the acceptable range for the total calorific input for maintaining desirable co-firing. Generally, the low heating value (LHV) of sludge is approximately one-fourth that of MSW. That ratio, however, depends on the moisture content of the sludge. The low heating value of the high-calorific industrial wastes used in this study was three times higher than that of the MSW. In our previous study, we burned industrial wastes without sludge [9]. In this study, the co-firing of paper sludge with synthetic leather wastes was tested. The temperatures inside the primary combustion chamber and at the exit of the secondary combustion chamber were measured along with the exhaust gas emissions.

2. Pilot-scale incinerator with flue gas treatment system

The incineration facility used in our study was located at a synthetic leather company in Cheon-an, Korea. The company produces a waste stream that includes useless synthetic fibers, synthetic leathers and plastics. Fig. 1 is a schematic diagram of the incinerator with the flue gas treatment system. The facility consisted of a waste feed system, primary combustion chamber (incinerator) employing a nozzle-type grate system, secondary combustion chamber, high-temperature heat exchanger for preheating the fresh air, waste heat boiler, dry-type reaction tower, bag house filter, blowers and control panel. The incinerator was originally constructed to burn industrial wastes. Its capacity was 160 kg/h. A pusher-type waste feeding system was used. The volumes of the primary and secondary combustion chambers which were 4.3 and 4.4 m^3, respectively, resulted in a residence time for the flue gas in the combustion chambers of over 2 s. The grates in the incinerator were divided into three stages: drying, reaction, and post-reaction stages. Wastes were periodically moved to the next stage by sliders. The exhaust gas passing through the waste heat boiler went through the dry-type reactor using a slaked lime and a bag house filter [10].

Fig. 2 shows the schematic diagram of the incinerator, which utilized a nozzle-type grate system, covered with ceramic castable and sliders to protect the nozzles from the flame. The nozzle-type grate system was fixed to the bottom of the furnace, and consisted of steel tubes (like nozzles), each of which had a tip hole, with diameter of 3–5 mm. If a conventional metal moving grate system had been used, the direct heat from the high-temperature flame could have caused damage to it. However, in our heat-resisting ceramic nozzle-grate system, hot preheated air could be used. This helped to reduce the high moisture content of the wastes.

This system also had advantages in relation to maintenance and repair work. The nozzle-type grate system was able to overcome the typical difficulties encountered with the use

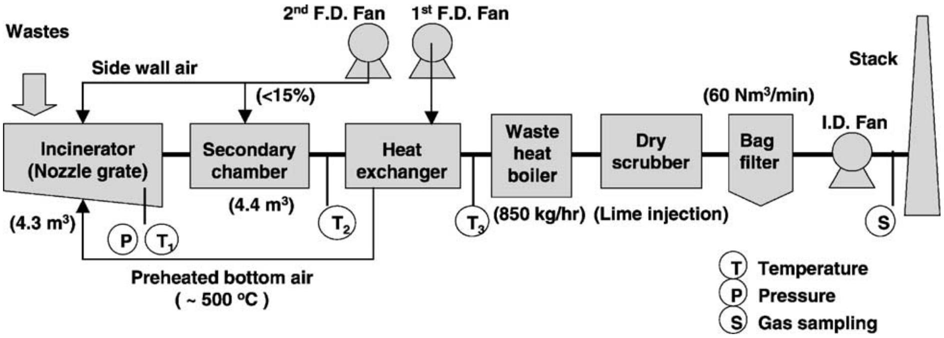

Fig. 1. Schematic diagram of the incineration facility used in this study.

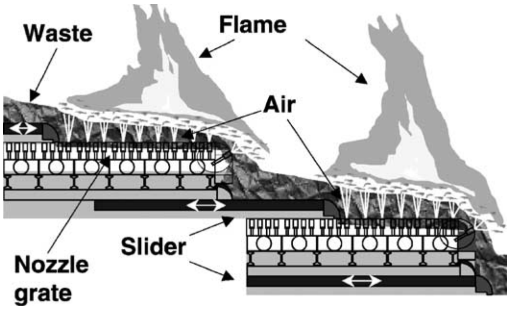

Fig. 2. Schematic diagram of the burning wastes on the nozzle-grate system.

of conventional metal grate systems for burning sludges, e.g. the falls-off of the unburned wastes and bottom ash through the gaps between grate bars, thermal transformation of metal grates, and corrosion and abrasion of the grates. The nozzle-type grate system we selected for our incinerator had less chances of sludge falling down due to the high air velocity through the nozzle tips.

A uniform heat input, i.e. waste throughput, is one of the most important factors for efficient incineration. With the small facility, due to the use of a pusher-type feeding system and the high-calorific value of the industrial wastes with short combustion time, uniform calorific input was possibly the key to good incineration achieved in this study.

3. Experimental

3.1. Experimental methods and conditions

The temperature, pressure and gas sampling points are shown in Fig. 1. The temperatures inside the primary combustion chamber and at the exit of the secondary combustion chamber were measured by R-type thermocouples. The primary chamber pressure was measured using a pressure transducer (Series T100, Hisco SI). The pressure was set to -5 mm H_2O. The concentrations of O_2, CO, NO and SO_2 in the flue gas were measured at the stack using a combustion gas analyzer (KM-9106, Kane-May). All the electrical signals from the thermocouples, the pressure transducer, and the gas analyzer were delivered through compensation cables and saved to a personal computer via an A/D converter (ADAM-4520, Advantech). The flow rates of the supply air were estimated based on the mean velocity measured in the air-supplying using a hot wire anemometer (Model 8384, TSI).

The combustion air was supplied into the furnace through two FD fans. The air injected to the bottom of the primary combustion chamber by the first FD was preheated to about 500 °C after passing through the heat exchanger by the hot exhaust gas from the incinerator. The preheated air was effective for drying the high moisture content wastes in order to help burn the wet sludge with high co-firing rates. The air supplied through the sidewall of the combustion chamber from the second FD fan was mixed with the combustible gas resulting in an extension of the retention time of the gas mixture. Industrial wastes, such as synthetic

Table 1
Summary of experimental conditions

Case no.	Mass of unit package (kg)		Feeding period (s)	Total waste input (kg/h)	Sludge co-firing rate (%)	Air flow (Nm^3/min)		Low heating value of the unit package[a] (kcal/kg)	Preheated temperature of bottom air (°C)	Calorific input through wastes[b] (kcal/h)	Recycled heat to the bottom air[c] (kcal/h)	Total calorific input[d] (kcal/h)
	Industrial wastes input	Sludge input				Bottom	Side wall					
1	6.0	0.0	135	160	0.0	12.0	12.2	5343	–	855900	–	855900
2	6.1	1.5	135	205	19.7	12.0	12.2	4384	–	889500	–	889500
3	6.2	2.7	135	240	30.3	12.0	12.2	3868	–	919200	–	919200
4	8.0	0.0	180	160	0.0	9.4	12.7	5343	532	854800	92800	947600
5	6.5	1.5	180	160	18.8	9.4	12.7	4431	506	709000	87800	796800
6	5.0	3.0	180	160	37.5	9.4	12.7	3520	454	563200	77600	640800

[a] Calculated from Eq. (1) and measured HHV of industrial wastes and sludge.

[b] Truncated after calculation from LHV and wastes input.

[c] Truncated after calculation from preheated temperature of bottom air and preheated airflows.

[d] Total calorific input (kcal/h) is the sum of calorific input through wastes (kcal/h) and recycled heat to the bottom air (kcal/h).

leathers, were discharged as a roll 2 m wide, so the pretreatment of the leathers to smaller parts for the unit packaging was necessary. The wet sludge was premixed with industrial wastes and packed in a unit package.

The experimental scenarios for this study are summarized in Table 1. The unit packages of 6–9 kg, containing industrial wastes and sludge, were fed into the incinerator every 135 or 180 s. The sludge co-firing rate represented the sludge fraction in the total wastes input. For Cases 1–3, the sludge input was varied, while the industrial wastes input was kept almost constant. For Cases 4–6, the sludge co-firing rate was varied, while the total waste input was fixed at 160 kg/h. The differences in the operating conditions between Cases 1–3 and Cases 4–6 were: the use of preheated air, and a slight disparity in the amount of supplied air as a result of the preheating from the heat exchanger. The total calorific input was calculated from the industrial wastes and sludge inputs and from the re-circulated heat added to the preheated fresh air. Whenever the experimental conditions were changed, the experiments were started following a 2 h equilibration period, where the temperatures and exhaust gas emissions were monitored until a steady state had established.

3.2. Properties of industrial wastes and sludge

To maintain an even temporal heat input, the object industrial wastes were restricted to synthetic leathers discharged from the company. Sludge was supplied from a paper manufacturing company located in Dae-jeon, Korea. These wastes were dewatered using a vacuum belt press.

Table 2 shows the results of the proximate and ultimate analyses of the industrial wastes and the paper sludge. A thermo-gravimetric analyzer (TGA, LECO-601) was used for the proximate analysis. From the high heating values (HHV), measured by a bomb calorimeter (LECO-AC350), the low heating values were calculated using the relation shown below. In this equation, 600 kcal/kg was used as the evaporation latent heat of the moisture and *H*

Table 2
Proximate and ultimate analyses of industrial wastes and paper sludge

Proximate analysis (wt.%)		Ultimate analysis (wt.%)		High heating value (HHV)	Low heating value (LHV)
Synthetic leather					
Water	1.87	C	59.09	5928.9 (kcal/kg)	5342.7 (kcal/kg)
		H	8.76		
Combustibles	92.73	O	29.56		
		N	1.98		
Ash	5.40	S	0.12		
		Cl	0.49		
Paper sludge					
Water	61.75	C	46.34	2364.8 (kcal/kg)	482.5 (kcal/kg)
		H	6.55		
Combustibles	21.17	O	38.14		
		N	8.97		
Ash	17.08	S	–		
		Cl	–		

and w represent the dry based hydrogen atom and water contents (wt.%), respectively:

$$\mathrm{LHV} = \mathrm{HHV}(1-w) - 600\{9H(1-w)+w\} \tag{1}$$

4. Results and discussion

4.1. Combustion and emission characteristics

Fig. 3 shows the temporal variations in the temperatures and exhaust emissions for Case 5 as a typical example of the experimental result. As shown in Table 1, 6.5 kg of leather wastes and 1.5 kg of paper sludge were mixed together in a vinyl bag as a unit package and fed into the furnace every 3 min. The sludge co-firing rate was 18.8% and the total waste input was 160 kg/h.

The averaged furnace temperature (T_1) was about 919 °C, and the temperature at the exit of the secondary combustion chamber (T_2) was 840 °C. Since the temperature variation was not large, the facility was considered to be in a steady state. The chamber pressure fluctuated slightly because it was sensitive to the rapid burning of the volatile materials from the industrial wastes. The mean pressure was slightly below 1 atm although the exhaust gas emissions, especially the O_2, show periodic changes over the 3 min waste feeding period, but the mean levels satisfy the emission regulation in Korean. Considering the wet sludge was burned without any auxiliary burner, the incineration process was satisfactory.

4.2. Limit of co-firing with total calorie input

In Figs. 4 to 7, the steady-state gas temperatures and exhaust gas emissions for all Cases (1–6) were reconstructed from raw data, as shown in Fig. 3. To obtain the correlations between the various experimental conditions, all the graphs were plotted based on the total calorific input.

Fig. 4 shows the average temperatures inside the primary combustion chamber, at the exit of the secondary combustion chamber and of the preheated air, for all the experiments. All the temperatures at the exit of the secondary combustion chamber (T_2) were higher than the 800 °C required, with the exception of Case 6, where the sludge co-firing rate was about 37.5%. All the preheated air temperatures (T_3) were greater than 450 °C, and were dependent on the flue gas temperature. This hot preheated air was favorable for drying the high moisture content sludges. It should be noted that the typical metal grate system has the limitation of using air preheated to a highest temperature of about 200–250 °C.

Fig. 5 shows the oxygen concentrations measured in the stack. The values and the error bars indicate the averages and their standard deviations, respectively. The average oxygen concentration decreased from 13.3 to 9.7% with increasing total calorific input. Fig. 6 shows that the average value of the CO emissions generally increased with increasing total calorific input. The increase in calorific input means the increase in wastes input, that is, the increase in the amount of combustibles. Therefore, it is apparent that the decreased O_2 and increased CO concentrations with increasing total calorific input were mainly due to the constant air flowrate.

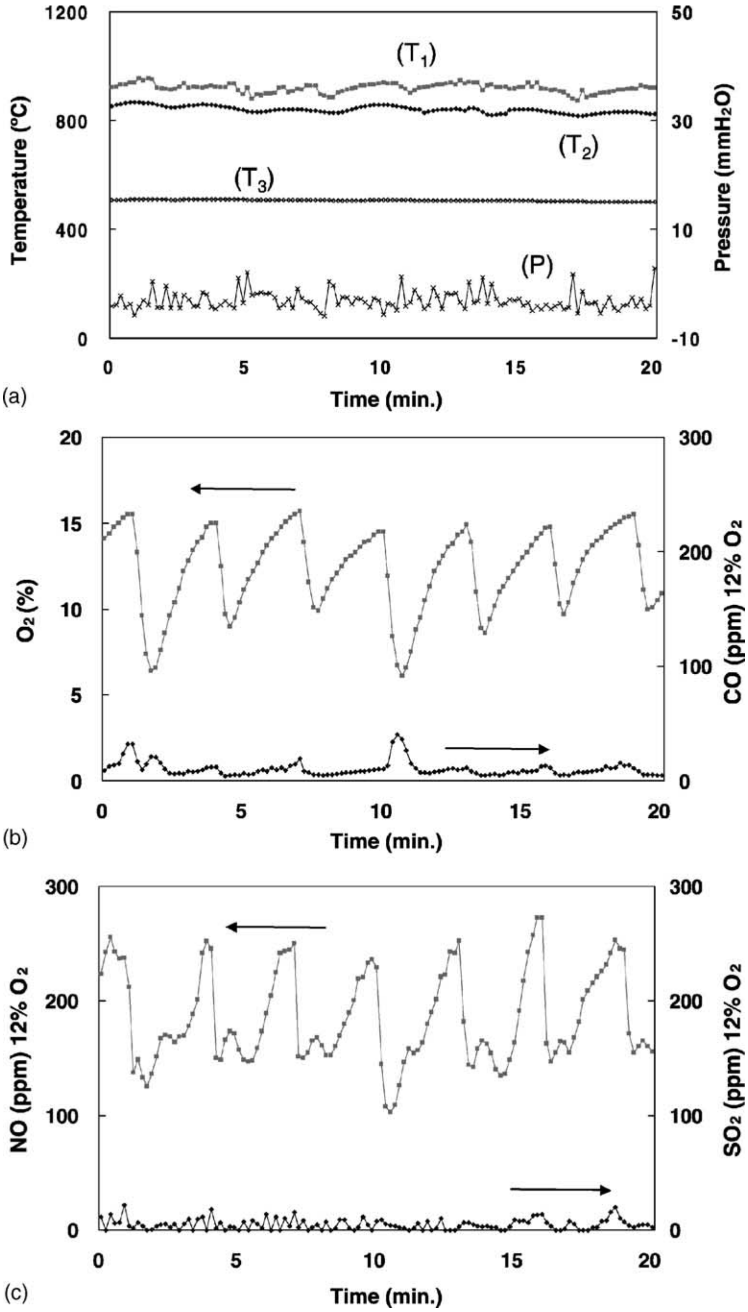

Fig. 3. Temporal variations of temperatures and emissions of the incineration facility (Case 5): (a) gas temperatures and pressure; (b) O_2 and CO concentrations; (c) NO and SO_2 concentrations.

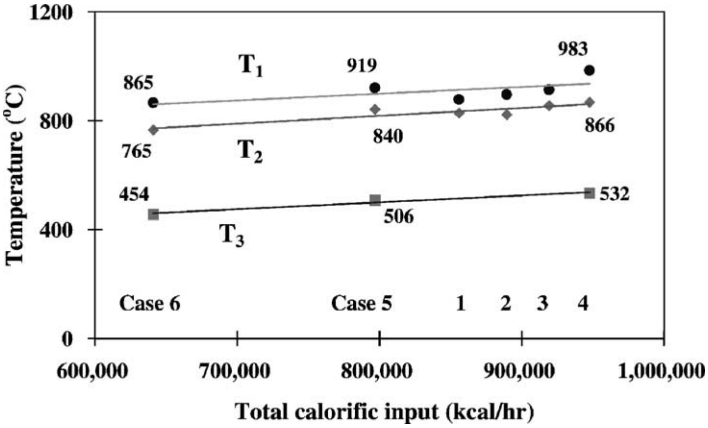

Fig. 4. Time-averaged temperatures of combustion chamber (T_1), exit of the secondary combustion chamber (T_2), and preheated air (T_3), with total calorific input.

The large standard deviation in the CO emissions for Case 4 requires an explanation. Case 4 corresponded to the experimental conditions of a relatively large unit package (8 kg), without sludge input. When using a smaller unit package (6 kg), also with no any sludge input and the same resultant total waste input (160 kg/h), Case 1 showed that the deviation in the CO emissions was much smaller than with Case 4. This result can be explained as follows: for the case of a large unit package, the constant supply of combustion air in the present experiment may not be sufficient for the local diffusion of oxygen into the combustible gases near the wastes and thus for the reaction required for the conversion of carbon to CO_2. Since Case 1 utilized smaller unit packages, and larger amounts of combustion air, the deviation in the CO emissions would be much smaller than in Case 4. It is also interesting to compare Cases 4 and 2. As with Case 1, Case 2 showed a much smaller standard deviation in the CO

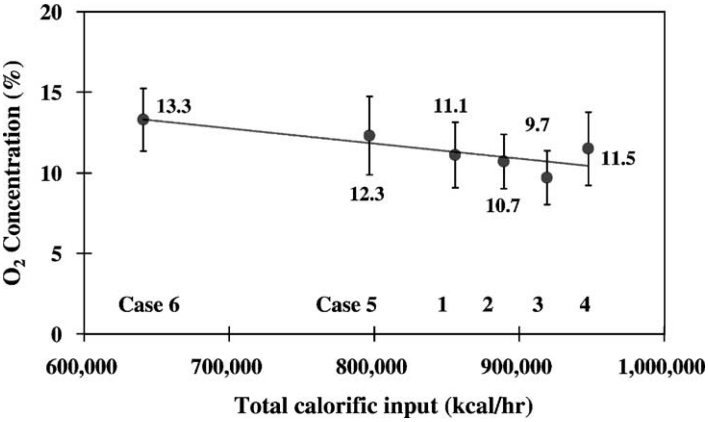

Fig. 5. Time-averaged O_2 concentrations and standard deviations with total calorific input.

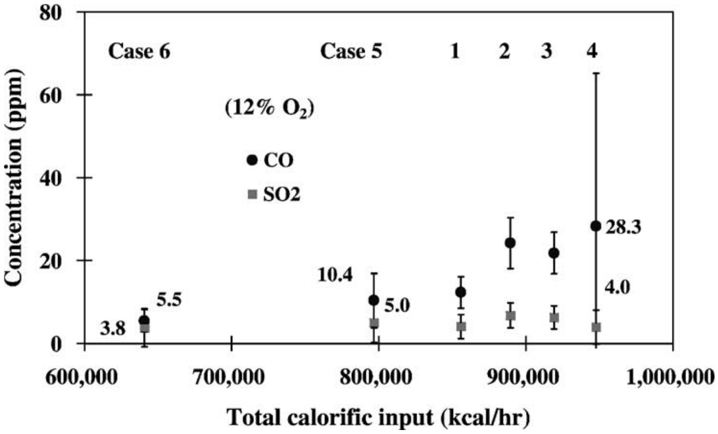

Fig. 6. Time-averaged CO and SO_2 concentrations and standard deviations with total calorific input.

emissions. Cases 2 and 4 utilized similarly sized unit packages, 7.6 and 8 kg, respectively, and thus have similar total calorific inputs, 889,500 and 947,600 kcal/h, respectively. The main difference between the two cases is the co-firing of the sludge. Fig. 6 suggests that sludge co-firing will help alleviate the fluctuations in the CO emissions.

With a constant total waste input of 160 kg/h (Case 4–6), Fig. 7 shows that the nitric oxide (NO) emissions increase with decreasing total calorific input. These results imply that there are greater NO emissions as the sludge co-firing rate increases. As shown in Table 2, a relatively high N content in the sludge can cause an increase in NO emissions with a higher sludge input. For Case 6, the NO emissions (232 ppm) exceeded the regulation 200 ppm. It should also be noted that Case 6, corresponding to the highest sludge co-firing rate (37.5%), does not comply with the temperature regulations, as discussed with Fig. 4.

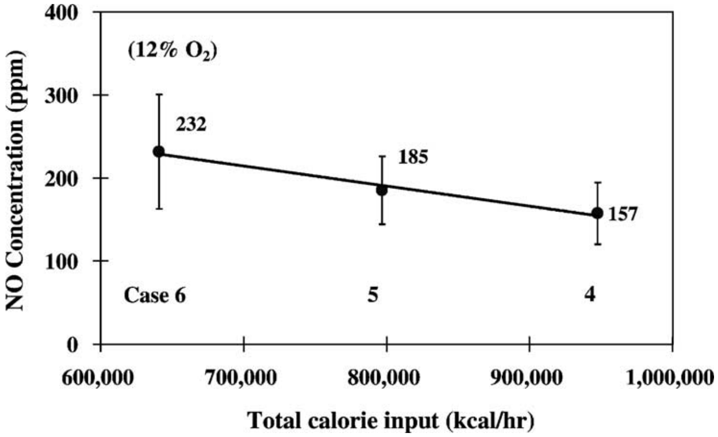

Fig. 7. Time-averaged NO concentrations and standard deviations with total calorific input.

5. Conclusions

Experiments on the co-firing of high-calorific industrial wastes, with paper sludge, were performed in a pilot-scale industrial waste incinerator employing a nozzle-type grate system. The temporal variations in temperatures and exhaust gas emissions were monitored, and used as parameters for determining desirable incineration. The results are summarized as follows:

1. The high CO emissions that were mainly due to the rapid vaporization of combustibles from high-calorific industrial wastes could be alleviated through the co-firing of sludge with the high-calorific industrial wastes.
2. Because of the high nitrogen content in the sludge, the increase in the co-firing rate caused higher NO emissions in the flue gas.

The temperature in the combustion chamber, the CO emissions, and the NO emissions, are among the three major constraints for the desirable co-incineration of sludge. Our results showed that, if the total calorific input was below 750,000 kcal/h, for 25–30% co-firing, the flue gas temperature of exiting the secondary combustion chamber might be lower than the 800 °C temperature regulatory limit. Other experimental cases resulted in matching the regulation well. Further case studies will be required on the different co-firing rates near the calorific limit.

Acknowledgements

The authors would like to thank the Ministry of Science and Technology, Korea, for their financial support.

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