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Thermal plasma treatment of stormwater detention pond sludge*

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Abstract: A thermal plasma treatment experiment was conducted on stormwater detention pond sludge. The original sludge compositions were analyzed by neutron activation multi-element analysis. Thirty-two elements were detected in the sludge samples, and nine of them were below detection limit. The assessment of Zn, As, Mn, and Fe concentrations against the Ontario Ministry of Environment's Sediment Quality Guidelines indicated a marginal-to-significant pollution, and the concentration of Cr presented a gross pollution. After thermal plasma treatment, the mean weight percentage removal at 0 and 2 L/min of air flow rates was 2.78 ± 0.51 and 3.85 ± 1.35 %, respectively. The maximum weight removal of 5.87 % was achieved with 2 L/min air flow rate and 2 h of treatment time. Reduction of total organic carbon (TOC) increased with increasing treatment time and air flow rate. Eight gas compounds, CO, CO_2, NO, NO_2, NO_x, SO_2, H_2S, and C_xH_y were measured and observed during the treatment process.

Keywords: thermal plasma; detention pond; sludge; neutron activation analyses; stormwater.

INTRODUCTION

Non-point source pollution is the pollution caused by sediments, nutrients, other organics, and toxic substances originating from various land use activities or directly deposited from the atmosphere. As opposed to point sources of pollution, non-point sources of pollution have no single, localized source. Common origins of urban non-point sources pollution include improperly sited, designed, and maintained onsite wastewater treatment (septic) systems, pet wastes, lawn and garden fertilizers and pesticides, household chemicals that are improperly disposed, automobile fluids, road deicing/anti-icing chemicals, and vehicle emissions [12]. During rainfall events, stormwater washes off the pollutants, which have been accumulating on urban surfaces and carries them downstream. To protect downstream receiving waters, stormwater detention or retention ponds, or constructed wetlands, are designed to contain and partly treat urban stormwater runoff [13]. These ponds are usually designed to trap and settle out solid materials carried by stormwater. This reduces contaminant loads discharged to rivers or lakes and improves water quality. While some contaminants will biodegrade within the pond or wetland, others are more persistent and can accumulate in the sediment (also referred to as sludge) at the bottoms of the stormwater ponds and wetlands.

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Urban land usage generates residual and waste materials from a myriad of individual and group activities. Typical urban stormwater includes pollutants such as sediments, pathogens, fertilizers, nutrients, hydrocarbons, and metals [10–12]. Each type of land use has unique characteristics that result in the generation of different types of pollutants. Density or intensity of the land usage and percent of imperviousness also affect the quantity of pollutants [7]. The following factors affect the detailed pollutant compositions of stormwater sludge:

- vehicular traffic
- lawn and garden maintenance
- air pollution
- municipal maintenance
- industrial and commercial activities
- illegal connections
- illegal disposal
- transportation spills
- construction activity
- pet wastes and litter
- combined sewer overflows
- runoff from driveways and parking areas

Stormwater sludge may have to be treated to nonharmful levels before ultimate disposal. In this work, thermal plasma treatment of detention pond sludge is experimentally investigated, and gaseous by-products are discussed in detail.

EXPERIMENTAL APPARATUS

A schematic of the plasma torch-type sludge treatment system is shown in Fig. 1.

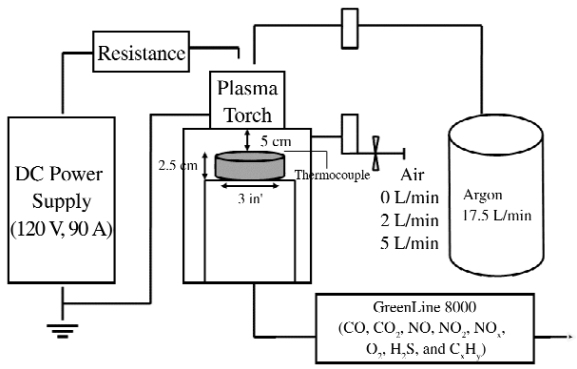


Fig. 1 Schematic of the plasma torch system.

Dried stormwater sludge was placed into a 99.8 % pure alumina made ceramic container with maximum operating temperature of 1950 °C in both oxidizing and reducing environments. The weights of sludge samples were mostly in between 20–30 g. A ceramic container with a diameter of 7.6 cm and depth of 5.1 cm was placed 5 cm below the torch. The heat was generated by a DC 10 kW plasma torch [2] and was ejected vertically through the top of the reactor chamber. Pure argon gas was used in the plasma torch, and air was injected into the reaction chamber to produce an oxidizing environment. Typical plasma melt reactor temperature is between 1100–1700 °C, depending on the plasma torch operating power [5]. The present treatment process of stormwater sediment was under nontransferred

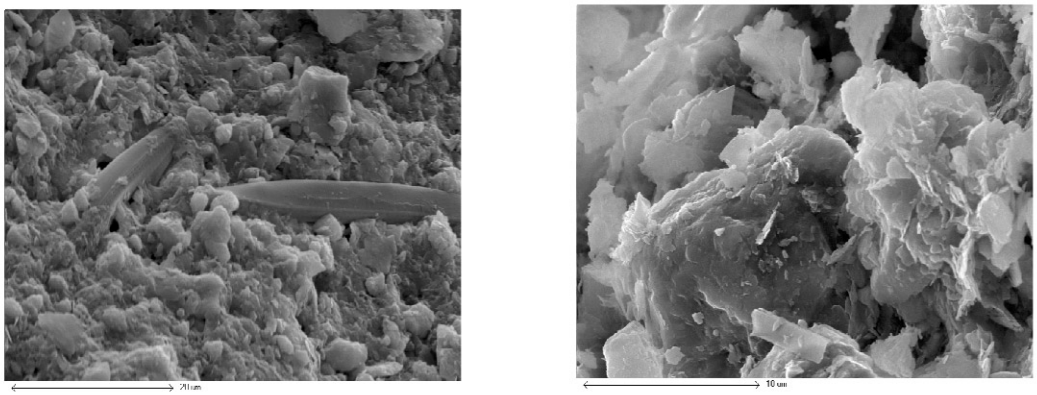
plasma operation mode. It provided slower heat transfer and conduction, hence detailed gaseous by-products generation mode could be investigated. A fixed argon gas flow rate of 17.5 L/min was injected into the torch without air for the creation of an anaerobic environment, and air flow rates varying from 2 to 5 L/min controlled by a flow meter were used for different oxidizing environments. Treatment times of 1, 1.5, and 2 h were examined for 0 and 2 L/min air flow rates, and 1 h for 5 L/min air flow rate. The operation conditions are summarized in Table 1. The exhaust gas was sampled downstream of the reaction chamber exit via a heat exchanger. The flue gas compositions were measured by combustion gas analyzer (Eurotron, Inc. GreenLine 8000), a portable emission gas analyzer which can measure O_2, CO, NO, NO_2, SO_2, C_xH_y, H_2S with electrochemical sensor and CO_2 and C_xH_y with infrared sensors.

Table 1 Operating parameters in thermal plasma treatment.

Current	90 A
Voltage	120 V
Power	1.5 kW
Argon flow rate	17.5 L/min
Air flow rate	0–5 L/min

PARTICLE SIZE DISTRIBUTIONS AND MORPHOLOGY

Physical analyses included the examination of the images of the treated sludge and reduction calculation after plasma treatments were conducted. The scanning electron microscopy (SEM) images shown in Figs. 2a and 2b are significantly different between the images before and after treatment. The two-phase structure in the stormwater sludge was crystallized after the treatment, and the long ellipsoidal structure that was obvious in the original sludge disappeared.



(a) (b)

Fig. 2 SEM image of original (a) and treated sludge (b) from Ancaster soccer field stormwater pond magnification of 4000 times, with argon flow rate of 17.5 L/min, air flow rate of 2 L/min in 2 h.

The weights of sludge before and after each treatment are summarized in Table 2. The maximum weight removal of 5.87 % was achieved with 2 L/min air flow rate and 2 h of treatment time. In general, the percentage of weight removal increases with longer treatment time and higher air flow rate. The mean weight percentage removals for 0 and 2 L/min air flow rates with various treatment times

were 2.78 ± 0.51 and 3.85 ± 1.35 %, respectively. Introducing oxygen into the system increases the oxidation of organic compounds, and thus results in a higher oxidation rate during the treatment.

Table 2 Weight removal by plasma treatment.

Air flow rate (L/min)	Time (h)	Weight before (g)	Weight after (g)	Percentage removal (%)
0	1	20.6	20.16	2.14
0	1.5	27.76	27.02	2.67
0	2	35.79	34.52	3.55
2	1	22.06	21.62	1.99
2	1.5	27.8	26.78	3.67
2	2	29.63	27.89	5.87
4	1	31.7	30.67	3.25

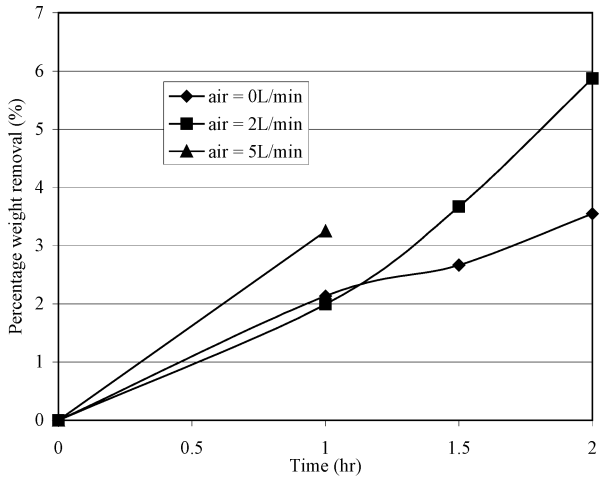


Fig. 3 Percentage weight removal with various air flow rates as a function of treatment time, with argon flow rate fixed at 17.5 L/min.

GASEOUS BY-PRODUCT ANALYSES

Total organic carbon (TOC) of the original and treated sludge was measured. First, all sludges were placed into an oven at 100 °C, then they were placed inside a pissicusor for 24 h in order to remove all the water content inside the sludge. The sediments were weighed before and after being placed into another oven at 550 °C for 30 min. Most of the organic compounds would be vaporized inside the oven, and, thus, the difference of weight would be the total amount of TOC in the samples.

The TOC of the stormwater sludge observed was 7.65 % by weight. The treated sludge of different air flow rates with respect to treatment time is shown in Fig. 3. The TOC in the treated sample by plasma was lower than the original TOC in stormwater sludge. The heat in the reactor oxidized the organic compounds in the sample into gas compounds, thus reducing the amount of TOC. In general, the TOC percentage in the sample decreases as treatment time increases. The organic compounds may be gasified by oxidation and/or reduction, and hence, the weight of the sample decreases. The samples still retain some TOC after the treatment, and the percentages of TOC are all above the lowest effect level (LEL) of the Ontario Ministry of Environment. The thickness of the sediment samples inside the reactor may affect the efficiency of the treatment under nontransferred plasma operating mode. Heat from

the plasma torch might only be able to reach the top part of the sample, and required longer time to reach the bottom part of the container. Since the organic part of the sediment was converted to gases, it is necessary to investigate the gas content of the outlet to prevent toxic gases from being emitted into the environment. Figures 4 and 5 show the typical main compositions of emission gas for air flow rates of 0 and 2 L/min with treatment times of 1 and 1.5 h, respectively. Eight gas compounds, including CO, CO_2, NO, NO_2, NO_x, SO_2, H_2S and C_xH_y, were analyzed. The oxygen levels inside the reactor are dependent on the air flow rates, thus, they were fixed during the experiment. The emission gas components in treatment with the absence of air are shown in Fig. 4. It showed that oxidation occurred for the first 30 min and pyrolysis started at 65 min after the treatment. Oxides in the sample were combusted and released oxygen for the reactions to produce NO_x, SO_2, and CO at the beginning, and as there was no oxygen applied to the system, pyrolysis started and may have converted some carbon and sulfur compounds to hydrocarbon and H_2S in gas phase near plasma–solid interfaces. Figure 5 shows a higher oxidation rate in the first 30 min of treatment with the presence of oxygen in the reactor. The concentrations of the oxides such as CO, NO, SO_2, NO_2, and CO_2 are much higher with the presence of air. Most of the oxides in the samples were combusted at the beginning. Since oxygen was provided constantly during the treatment, oxidations continued in the later part of the treatment, and thus a constant amount of oxides was generated during the later part of the treatment.

The result clearly shows that the carbon and sulfur compounds in the sludge were oxidized into gaseous compounds during the treatment. The generations of NO, NO_2, and NO_x might be from the nitrogen compounds in the sample. The concentrations of CO, NO, NO_2, SO_2, CO_2, and C_xH_y were much higher in an oxidizing environment. It is reasonable that the generation of most of the oxides such as SO_2, NO, NO_2, NO_x, and CO_2 in 5 L/min of air flow rate were in the highest concentration as there was more oxygen provided for the oxidation. It was observed that CO concentrations increased with increasing oxygen. The increased oxygen concentration in the chamber had a direct effect on the CO concentration [1]. Most of the CO was formed by dissociation, via negative ions or electrons of CO_2. The increase in concentration of CO might be caused by the increased availability of CO_2 from the increased air flow rate [2–4]. NO_2 and CO_2 were not produced, while H_2S and C_xH_y were generated in the pyrolysis stage, which occurred after 1 h with the absence of air. Hydrocarbons and sulfur were easier to react to the oxygen released by the oxides than nitrogen, thus the production of CO and SO_2 was more prevalent in the early oxidation stage. The generation of H_2S was at the highest in the pyrolysis stage with the absence of air.

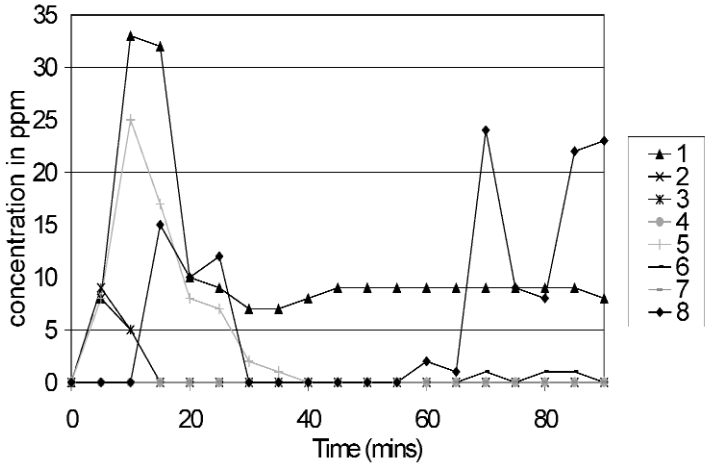


Fig. 4 Emission gas components for air flow rate of 0 L/min and argon flow rate of 17.5 L/min in 1.5 h. (1- CO ppm; 2- NO ppm; 3- NO_x ppm; 4- NO_2 ppm; 5- SO_2 ppm; 6- H_2S ppm; 7- CO_2 ppm; 8- C_xH_y ppm).

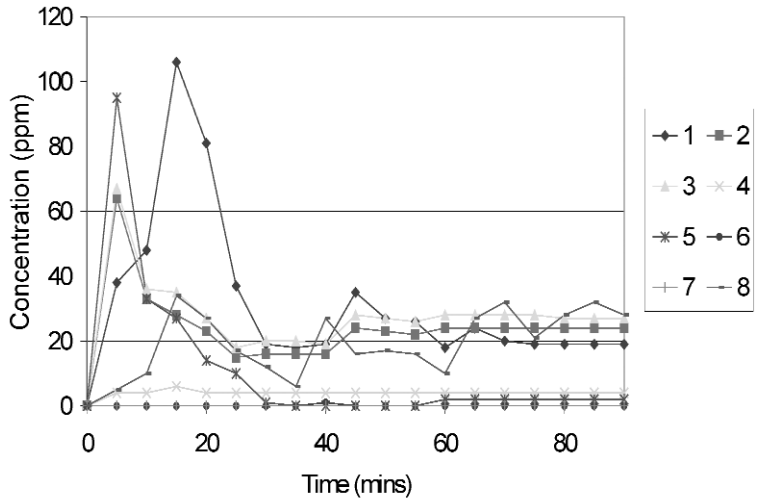


Fig. 5 Emission gas components for air flow rate of 2 L/min and argon flow rate of 17.5 L/min in 1.5 h. (1- CO ppm; 2- NO ppm; 3- NO_x ppm; 4- NO_2 ppm; 5- SO_2 ppm; 6- H_2S ppm; 7- CO_2 ppm; 8- C_xH_y ppm).

The generation of hydrocarbon was at the highest for air flow rate of 2 L/min. Hydrocarbon compounds are easier to oxidize to CO or CO_2 if sufficient air is provided, and thus the generation of hydrocarbon for air flow rate of 5 L/min was quite low compared to smaller air flow rates.

Although the weight removal reached maximum with the presence of air, more toxic gas compounds were produced with increasing air flow rates. Maximization of the efficiency of weight removal and minimization of the amount of toxic gas emission must be considered.

The concentrations of flue gas emitted from plasma treatment are compared to the guideline for combustion and air pollution requirements for new municipal waste incinerators from the Ontario Ministry of the Environment [8]. Although this guideline is not designed for stormwater sludge thermal plasma treatment, it can serve as a reference for the level of toxicity of the flue gas. Table 3 shows the parameters and emission limits of the guideline. The concentration of SO_2 in the flue gas with the absence of air was above the limit, and the concentrations of SO_2, NO_x, and hydrocarbon in the flue gas with air flow rate of 2 L/min were all above the emission limits. The concentrations of SO_2 and NO_x in flue gas with air flow rate of 5 L/min were above emission limits. An efficient removal of these toxic gases must be considered in the development of treatment processes.

Table 3 Parameters and emission limits of the Ontario Ministry of Environment, Canada (2004).

Parameter	Emission limit (ppm)
NO_x	110
SO_x	21
HCl	18
Organic matter	100 (undiluted)

ELEMENTAL ANALYSES

The element analyses were conducted by neutron activation analysis (NAA). The comparison of main (concentration > 1000 ppm), minor (concentration between 100 and 1000 ppm), and trace (concentration < 100 ppm) compositions between treated and original sediment samples are shown in Figs. 6–8, respectively. As expected, the presence of major elements was similar to that of the sediment prior to the treatment, but in different concentrations and enrichments. For major compositions, the concentrations of Mg, Cl, and Na for air flow rates of 2 and 0 L/min increased by 174 and 88 %, 105 and 133 %, and 83 and 61 %, respectively; while the concentrations of K and Ca under the two different air flow rates decreased by 23 and 35 %, and 12 and 2%, respectively. For minor compositions, the concentrations of Cr, Sr, Ba, and Mn fluctuate between 10–50 % while Zn decreased by 25 and 29 %, respectively, with the presence and absence of air. Enrichments of trace elements were observed after the treatment, with the exceptions of As and Nd. As observed from Figs. 6–8, a deviance between main concentrations of elements does occur under oxidizing and reducing environments. This can be explained by the fact that in the presence of oxygen the formation of binary or tertiary oxides greatly decreases the volatilization of metals [9].

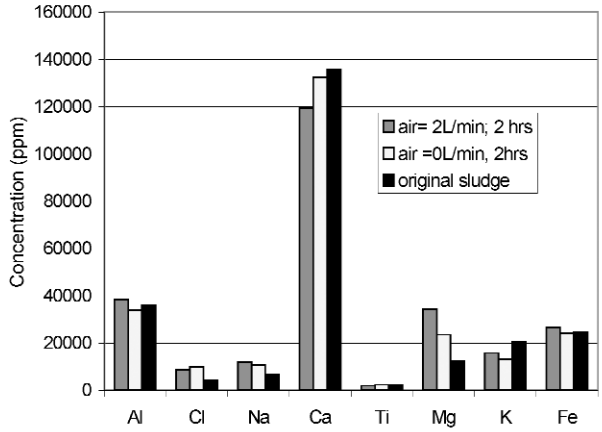


Fig. 6 Comparison of main compositions between treated sludge (air = 2 L/min and 0 L/min in 2 h, argon flow rate fixed at 17.5 L/min) and original sludge.

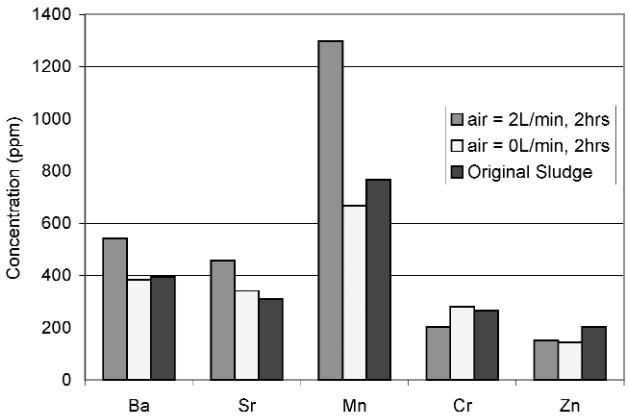


Fig. 7 Comparison of minor compositions between treated sludge (air = 2 L/min and 0 L/min in 2 h, argon flow rate fixed at 17.5L/min) and original sludge.

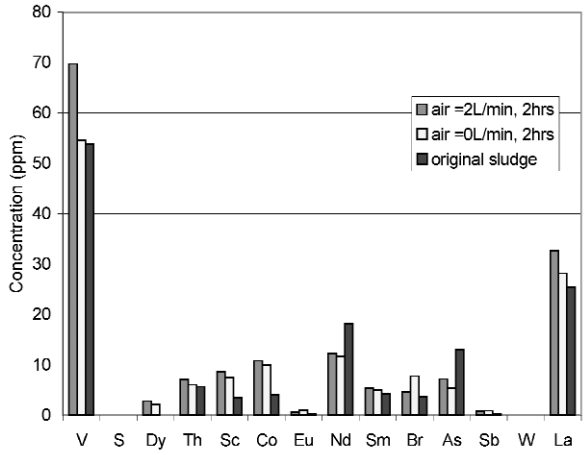


Fig. 8 Comparison of trace compositions between treated sludge (air = 2 L/min and 0 L/min in 2 h, argon flow rate fixed at 17.5 L/min) and original sludge.

Zn, K, and Nd are very volatile and decreased in concentration after the treatment. Conversely, Na and Cl, being two of the most volatile elements, increased in concentration instead. Elements exist in different chemical forms, whether pure metals, oxides, sulfites, carbonates, chlorides, hydroxides, or other [6], and volatility depends on the chemical form of the elements.

CONCLUDING REMARKS

A thermal plasma treatment experiment was conducted for stormwater sediment samples taken from a pond located in a highway/commercial area (Dartnell, Hamilton, Ontario). The mean weight percentage removal by plasma treatment for 0 and 2 L/min of air flow rate was 2.78 ± 0.51 % and 3.85 ± 1.35 %, respectively. The maximum weight removal of 5.87 % was achieved with 2 L/min air flow rate and 2 h of treatment time. After the treatment, the two-phase structure in the stormwater sludge was crystallized and only one structure was left in the sediments. The TOC in the plasma-treated sample was lower than the original TOC in stormwater sludge. TOC percentage in the sample decreased with longer treatment time. Eight gas compounds including CO, CO_2, NO, NO_2, NO_x, SO_2, H_2S, and C_xH_y emitted during the treatment process. The thermal plasma treatment that operated in an oxidizing environment yielded more oxides; while the process that operated in a reducing environment yielded fewer oxide compounds and no NO, NO_2, or CO_2.

Based on the present investigation, the next-generation mobile thermal plasma sludge treatment system can be near zero emission as shown in Fig. 9. The proposed experiment includes two parts: (1) thermal plasma decontamination of stormwater sediment and (2) pulsed arc electrohydraulic discharge (PAED) for sludge-water treatment. After dredging, the stormwater sludge will be spread on top of a filter. The solid component will be transferred to a thermal plasma reactor, while the filtered sludge-water will be subjected to PAED treatment. As in the present investigation, one of the approaches (left-hand side of Fig. 9) with less electrical power requirement under nontransferred plasma modes can decontaminate stormwater sludges without melting and just focusing on removal of TOC, and hence, the removal of volatile organics and chemical and biological contaminants and produce clean sludge that could be used as land-fill materials. The other approach (bottom of Fig. 9) with slightly higher electrical power requirements under transferred plasma mode, provides higher heat transfer and conduction rate to melt the stormwater sludge and form unleachable slags with separated metal layer at the bottom, as it has been demonstrated in the commercial municipal incinerator plasma ash melting system [14–16] for recycling. Unlike municipal sludges, which contain a much higher TOC content (35–50 %) suitable

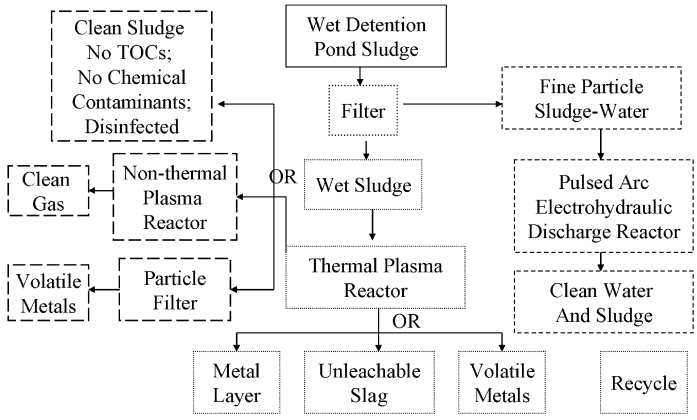


Fig. 9 Proposed mobile thermal plasma sludge treatment system.

for self-combustion and melt under relatively high gas temperature in the commercial system [19–20], the present investigation showed only 5–8 % of TOC in the stormwater pond sludges. Hence, thermal plasma may be one of the few options to treat the stormwater pond sludges in remote sites. Regardless of which approach is taken, the gaseous emission and sludge-water should be treated before emissions. The smaller power requirement, the nonthermal plasma flue gas treatment [14,17], and PAED water treatment [14,18] are recommended in the mobile system. The economic analyses will be conducted based on the pilot plant studies in the future.

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