DOI: 10.51975/SRCX6538
Journal of the Nigerian Society of Chemical Engineers, 36(1), 2021

APPLICATION OF LOW-TEMPERATURE THERMAL ARC PLASMA REACTOR FOR PETROLEUM INDUSTRY WASTEWATER SLUDGE TREATMENT

***Abubakar M. A[1], Abdulkarim, B. I.[2] and Kefas, E. G.[3]**
[1,3] Department of Chemical Engineering, Kaduna Polytechnic, Kaduna, Nigeria
[2] Department of Chemical Engineering, University of Abuja, Nigeria
E-mail: abualimoh67@gmail.com, balisa76@yahoo.com & egkefas@yahoo.com

ABSTRACT
A large quantity of wastewater sludge is generated yearly. Traditional disposal methods are short of providing the much needed benign treatment. Thermal plasma is a promising treatment technique to address this problem. A 20 cm^3 capacity laboratory-scale thermal-arc plasma reactor was developed using a 4.5 kW TIG welding torch and was used to treat wastewater sludge. The design was based on a DC transferred-arc torch with argon gas as plasma forming gas. The reactor was tested with wastewater sludge from the petroleum industry. The plasma arc temperature was in the range of 356 – 1694 ^oC at an arc current of 100 – 190 A. Two products, flue gas and a vitreous slag were obtained. A mass reduction of 36.87 – 91.40% of the sludge was achieved at an arc current 150 – 190 A, which correspond to a plasma temperature range of 539 – 1603 ^oC. The mass reduction increased with treatment duration from 2 – 8 min. The mass reduction also increased with increasing arc current from 150 – 190 A at an interval of 20 A. Reduction in total organic carbon (TOC) was between 74.03 – 75.83%. The metal elements in the wastewater sludge were enriched after the plasma treatment. The composition of the flue gas is H_2, CO, O_2, CO_2, CH_4 and C_2 hydrocarbons. CO is the major component accounting for over 74%. The concentration of greenhouse gases (CH_4 and CO_2 combined) is less than unity. The system was able to gasify the organics in the wastewater sludge to combustible gases and vitrified the inorganics into a slag.

***Keyword**: Thermal plasma, wastewater sludge, plasma temperature, mass reduction, TOC, carbon conversion*

1. INTRODUCTION

Thermal arc plasma technology has become a prominent waste treatment technique for a wide variety of waste because of the shortcomings of traditional waste disposal methods (Ali *et al.*, 2016). The plasma arc treatment technology has been identified as a potentially effective tool for producing less harmful by-products which can be used in building and road construction (Kourti *et al.*, 2011; Tu *et al.*, 2008). The innovative plasma technique involves subjecting waste material to high-temperature arc plasma such that the organics and the volatile species are gasified while the inorganics and non-volatiles are chemically bonded in a vitreous matrix, thereby making them resistant to leaching of heavy metals (Agon, 2015). Thermal arc plasma provides a suitable treatment technique for special waste disposal requirements. Advantages of thermal arc plasma treatment technique over conventional incineration include high-temperature regime, high waste volume reduction, low gas throughput, process flexibility in either oxidizing or a reducing environment, and can effectively treat a wide variety of waste types (Heberlein, 2002).

There is an increase in the documented research, in the last two decades, concerning the destruction of hazardous wastes using thermal arc plasma technique. The growing interest of academic research in such an area cannot be unrelated to the ability of the technique to reduce waste volume by over 80% and produce benign byproducts (Ali *et al.*, 2016; Heberlein and Murphy, 2008). The plasma gasification of the organic portion of sludge has attracted interest as a source of energy and spawned process developments for the treatment of sludge from different sources (Bień *et al.*, 2013; Celary and Sobik-Szołtysek, 2014; Cubas *et al.*, 2014; Kim and Park, 2004; Leal-Quirós and Villafañe, 2007; Li *et al.*, 2007; Li *et al.*, 2012; Li *et al.*, 2015a; Li *et al.*, 2015b; Mohai and Szépvölgyi, 2005; Mountouris *et al.*, 2008; Ramachandran and Kikukawa, 2002; Shie *et al.*, 2014; Sobiecka and Szymanski, 2014). Factors like treatment efficiency, plasma gas flow-rate, the treatment period of a batch operation, feed flowrate of continuous operation and inter-electrode separation were the subject of investigation.

DOI: 10.51975/SRCX6538
Journal of the Nigerian Society of Chemical Engineers, 36(1), 2021

Feasibility studies involving design and fabrication of thermal arc plasma reactors for hazardous waste destruction are also documented in the literature. In the USA a laboratory-scale thermal arc plasma reactor consisting of a highly instrumented furnace equipped with a 75 kW transferred arc plasma torch, was developed and used to study the physical and chemical behaviour of metal-spiked waste (nickel and chromium) in a high-temperature plasma regime (Cortez *et al.*, 1996). In Thailand, a 20 kW laboratory-scale, atmospheric-air DC plasma reactor was designed and fabricated using a non-transferred plasma torch and its performance was evaluated using electronic waste (Tippayawong and Khongkrapan, 2009). A research team in Brazil developed a small-scale, continuous-flow plasma reactor consisting of a torch with graphite electrodes and an integrated nebulization furnace. The reactor was used to eliminate carbon-tetrachloride from liquid waste (Cubas *et al.*, 2005). In the Durgapur city of West Bengal, a 20 kg/hr plasma reactor for the treatment of waste plastic was developed, and its performance on the pyrolysis of waste plastic and energy generation was studied (Punčochář *et al.*, 2012). Other similar studies involving the design and evaluation of thermal plasma reactor for hazardous waste destruction were reported (Barcza, 1986; Khongkrapan *et al.*, 2013; Szałatkiewicz *et al.*, 2012, 2013; Tang *et al.*, 2003; Townsend and Oehmig, 2014; Zhao *et al.*, 2001).

It is obvious from the above discussion that waste treatment using thermal plasma technology has gained ground, and laboratory/pilot scale plasma reactors have been developed and their performances for the destruction of hazardous waste were studied. However, to the knowledge of the authors, any attempt to develop a thermal arc plasma reactor that treats wastewater sludge from the petroleum industry it not available. The wastewater sludge from the petroleum industry is unique in its composition due to the presence of hydrocarbons, phenols and dissolved minerals (Diya'uddeen *et al.*, 2011). Thus, the present investigation was geared towards bridging this gap. In this study, a 20 cm^3 capacity laboratory-scale thermal-arc plasma reactor was developed and used to treat wastewater sludge from the petroleum industry.

2. MATERIALS AND METHOD

2.1. Thermal Plasma Reactor

The thermal plasma process system consists of a DC power source, a transferred arc plasma torch, a reaction chamber and a gas cooling and cleaning system. The process flow diagram of the system is shown in Fig.1. The equipment power rating and reactor capacity were based on a commercially available torch and 20 cm^3 of sludge respectively. The DC power source is a TIG (master weld, model: TP-2000) used commercially for arc welding, it supplies a voltage of 63 V and a variable current of 5 – 200 A to the plasma torch.

The transferred arc plasma torch was a Ø 2.4 mm tungsten rod (98% purity) inserted into the centre of a nozzle ejector. The torch was connected to the negative terminal of the DC power source. The nozzle ejector had an orifice opening through which argon gas (the plasma forming gas) flows. The torch was supported vertically at 10 cm distance above the anode electrode. The anode was a tungsten rod of Ø 10 mm and 35 mm length, placed concentrically at the centre of the reaction chamber. The reactor furnace was an aluminium block with a sculptured conical shaped chamber at the inner side and a cooling water jacket surrounding the chamber. The block had a dimension of 99 mm by 95 mm rectangular bottom and a height of 116 mm. The conically shaped chamber had a dimension of Ø 42 mm top, Ø 13 mm base and 20 mm depth. The furnace had a flue gas outlet and a glass window for temperature measurement. The gas cooling and cleaning system consisting of a cooling coil and particle gas filter were connected to the gas outlet. Photographs of the equipment components and the reactor setup are shown in Plate I. Specifications for TIG master weld and reactor system are shown in Tables 1 and 2 respectively

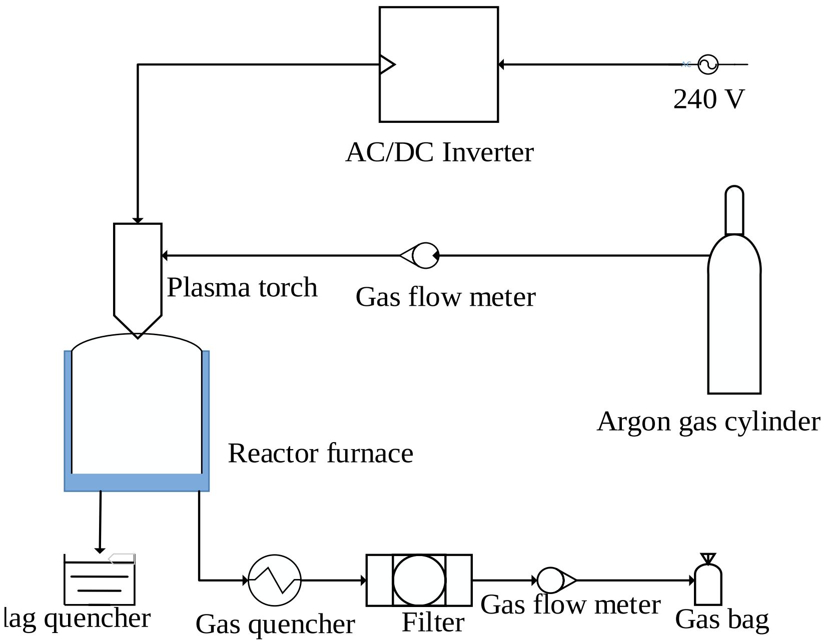

Fig. 1: Process flow diagram of the setup for plasma treatment of sludge

(a) The torch (b) reactor furnace (c) assembled chamber (d) complete setup

Plate I: Photographs of the equipment components and the reactor setup

Table 1: TIG master weld specifications

Specification	Input rating	Output rating
Model	TP – 2000	
Efficiency (%)	80	
Power (kW)	4.7	
Voltage (V)	220/230/240	63
Current (A)	31	5 – 200

2.2. Plasma Treatment of the Wastewater Sludge

A current of 100 A and argon flow-rate of 10 L/min were supplied to ignite and generate the arc plasma. The supplied current was increased gradually using a control nob while the plasma temperature was measured at intervals using an infrared thermometer (temperature range of 200 – 2200 ºC). The same procedure was repeated with argon flow-rate of 5 L/min and 15 L/min. The result of temperature measurement is presented in Fig. 2. Samples of wet wastewater sludge were treated batch-wise in the thermal arc plasma generated at arc currents of 150, 170 and 190 A respectively. At each of the operating current 20 cm^3 of the sludge was treated for 2, 4, 6, 8 and 10 min respectively. The flue gas, after passing through the cooling coil and the particle dust filter, was collected in a Teflon gas bag and analyzed in an offline residual gas analyzer (model: MKS Cirrus 2). The reactor was allowed to cool to room temperature. The slag collected, weighed and analyzed using TOC analyzer (Model SSM-5000A) and AAS machine (model: Perkin Elmer, PinAAcle 900T).

Table 2: Reactor parts and specifications

Reactor furnace: rectangular aluminium block
Dimension: 99 mm by 95 mm bottom, 116 mm height
Reaction chamber: conical shape
Dimension: Ø 42 mm top, Ø 13 mm base and 20 mm depth
Reactor inner volume: 20 cm^3
Cathode: long tungsten rod (98% purity)
Dimension: Ø 2.5 mm and length 150 mm

DOI: 10.51975/SRCX6538
Journal of the Nigerian Society of Chemical Engineers, 36(1), 2021

Anode: tungsten rod (98% purity)
Dimension: Ø 10 mm and length 35 mm

3. RESULT AND DISCUSSION

3.1. Plasma Arc Temperature Profile

The thermal arc plasma ignited at an arc current of 100 A, bellow 100 A only vibration was observed. At an argon gas flow-rate of 15 L/min, when the plasma arc current was increased from 100 – 190 A, the plasma arc temperature increased from 356 – 1694 °C. This increase in temperature was not uniform all through. Between 100 – 140 A, the increase in temperature was gradual, from 372 – 627 °C respectively. However, from 140 – 190 A, the plasma arc temperature increased from 627 – 1694 °C. This trend of increased plasma arc temperature with increased plasma arc current was equally observed with argon gas flow-rate of 10 and 5 L/min as depicted in Fig 2. The plasma temperature also increased when the argon gas flow-rate increased from 5 – 15 L/min.

Kim *et al.* (2003) reported a temperature of range of 1520 – 1570 K in a steam plasma used for the treatment of polychlorinated biphenyls (PCBs). Similarly, Tang and Huang (2005) observed an increased in temperature from 1073 – 1773 K in a high-frequency (HF) plasma reactor used for pyrolysis of waste tyre powder. In both the two literature results, an increased in the plasma temperature with increased arc current were reported.

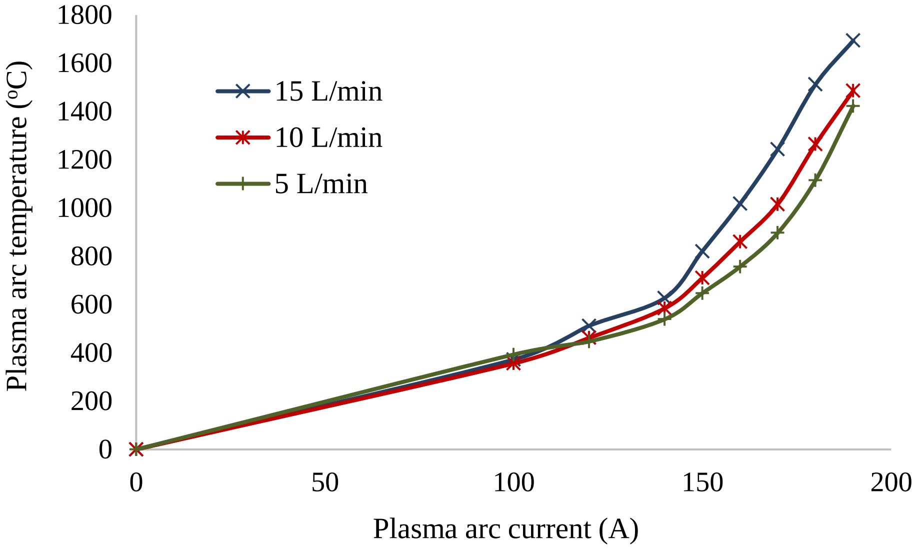

Fig. 2: Effect of plasma arc current and gas flow-rate on plasma temperature

3.2. Mass and Volume Reduction

The mass reduction achieved through the thermal plasma treatment of wastewater sludge from the petroleum industry was in the range of 36.87 – 91.40%. The obtained mass reduction was achieved at a relatively high plasma arc current (150 – 190 A). At 150 – 190 A, the plasma temperature ranges between 539 – 1603 °C. The high-temperature plasma environment decomposed the bulk of the sludge (the organic fraction) leaving behind small fraction (the inorganic) as a byproduct. There is a general increase in the mass reduction of the wastewater sludge with an increase in the plasma treatment duration as shown in Fig 3. At a plasma arc current of 190 A, the mass reduction increased from 44.78 – 91.40% when the plasma treatment duration increased from 2 – 10 min. Likewise, at 170 and 150 A, the mass reduction increased with increased plasma treatment duration.

The increase in the mass reduction is associated with the elevated temperature in the thermal plasma regime coupled with the limited amount of oxygen in the reaction chamber. The hydrocarbons in the wastewater sludge were gasified in the reducing environment by the elevated temperature plasma, into flue gases. Thereby, leaving the inorganics and heavy metals in the vitreous slag. The mass reduction was most significant between the 2nd and the 8th min, suggesting that the hydrocarbons were mostly gasified within the first 8 min of treatment. Similarly, mass reduction increased with increasing arc current from 150 – 190 A at an interval of 20 A. At constant applied voltage, the current is proportional to the power. Thus, higher arc current leads to a higher power, which yielded more decomposition of the hydrocarbons.

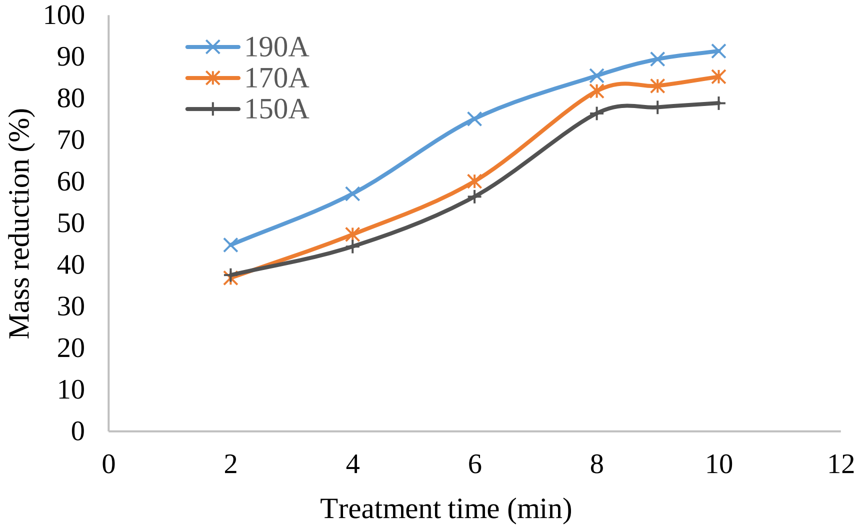

Fig. 3: Effect of treatment duration and arc current on mass reduction of sludge

3.3. Total Organic Carbon and Metal Composition

The measurement of the total organic carbon (TOC) in both the wastewater sludge and the product slag was conducted via the Total Organic Carbon-Solid Sample Module (TOC-SSM) machine (Model: SSM-5000A) (Ali *et al.*, 2017). Glucose was used as a standard for total carbon (TC) measurement while sodium carbonate was used as a standard for inorganic carbon (IC) measurement. Finally, TOC was calculated as the difference between the results of the measurements of TC and IC. The effectiveness of the thermal plasma reactor in treating the wastewater sludge was evaluated by determining the percentage carbon conversion using Equation 1. Carbon conversions of 74.03%, 75.83% and 75.86% were achieved with 150, 170 and 190 A respectively as shown in Table 3. These high carbon conversions are evidence of effective gasification of the hydrocarbon in the wastewater sludge by the thermal plasma. A similar result was reported by Li *et al.* (2015a) where a 100% carbon conversion of hydrocarbons was obtained when stormwater sludge was treated in an integrated thermal plasma system.

$$Carbon\ conversion(\%) = \left[1 - \frac{TOC\ of\ product\ slag}{TOC\ of\ sludge}\right] \times 100 \quad (1)$$

Table 3: Carbon conversion achieved in the treated wastewater sludge

Plasma arc current	TOC of sludge (%)	TOC of product slag (%)	Carbon conversion (%)
150	54.48	14.15	74.03
170	54.48	13.17	75.83
190	54.48	13.15	75.86

DOI: 10.51975/SRCX6538
Journal of the Nigerian Society of Chemical Engineers, 36(1), 2021

The metal concentrations in both the raw wastewater sludge and the product slag were determined via acid digestion according to US EPA method 3050 B as reported by Ali *et al.* (2019), the results are shown in Table 4. The metal elements in the wastewater sludge in major quantities were Al, K and Fe. Three other metal elements, Na, Mg and Zn were in small quantities while Cr, Mn, Ag and Hg were in trace quantities. After the thermal plasma treatment, the concentrations of the metals elements, except K, were significantly increased. The presence of large quantities of hydrocarbons in the wastewater sludge suppressed the concentration of the inorganics. After the gasification of the hydrocarbons, the inorganics became paramount in the products. The reduced concentration in the case of K could be as a result of vapourization of the metal because of its low melting point when compared with the other metals present.

3.4. Flue Gas Analysis

The composition of the flue gas obtained from the plasma treatment of wastewater sludge from the petroleum industry is shown in Table 5. The gas consists of H_2, CO, O_2, CO_2, CH_4 and C_2 hydrocarbons. The CO is the major component accounting for over 74%. At high temperature and in the presence of moisture (H_2O) hydrocarbon was converted to CO through water-gas reaction as shown in Equation 2. The concentration of oxygen in the flue gas is between 15 – 19%. There was the possibility of air getting into the reactor since it was not airtight. Concentrations of greenhouse gases (CO_2 and CH_4 combined) was very low, less than 1%. Even though there may be oxygen in the system, CO_2 was not stable at a temperature above 1400 ^oC and any quantity formed at the beginning of the process, when the temperature was lower than 1400 ^oC, may be converted to CO through Boudouard reaction shown in Equation 3.

$$C + H_2O \leftrightarrow CO + H_2 \quad (2)$$

$$C + CO_2 \leftrightarrow 2CO \quad (3)$$

Table 4: Metal concentrations in the wastewater sludge and the product slag

Metals	Concentration (ppm)	
	Wastewater sludge	Product slag
Na	21	34.4467
Mg	15.09	27.9125
Al	95.83	193.047
K	183.667	75.2154
Cr	1.6197	2.05181
Mn	0.1372	0.3487
Fe	327	620.989
Zn	12.4	25.5033
Ag	0.4630	0
Hg	1.3908	0.34387

Table 5: Composition of the flue gas

Component	Concentration (mol %)	
	1st run	2nd run
H_2	0.0051	0.0023
N_2	1.1729	1.3976
CH_4	0.5083	0.5125
CO	78.1940	74.5410
C_2^+	0.0195	0.0140
O_2	15.6388	18.6352
Ar	1.9549	1.8635
CO_2	0.0782	0.1398
NO_2	0	0.0056
SO_2	0.0043	0

4. CONCLUSION

A laboratory-scale thermal arc plasma reactor was developed to treat 20 cm^3 of wastewater sludge from the petroleum industry. The reactor was used to treat petroleum waste-water sludge. Temperature profile inside the plasma reactor increased with an increasing arc current and also with an increasing argon gas flowrate. A mass reduction of between 36.87 – 91.10% was achieved at a plasma temperature of 539 – 1603 ^oC. The mass reduction increased with an increase in the duration of treatment. The mass reduction also increased with an increase in plasma arc current from 150 – 190 A. A TOC reduction of 74.03%, 75.83% and 75.86% was obtained at an arc current of 150, 170 and 190 A respectively. The concentration of metals in the wastewater sludge increased after the plasma treatment. CO is the major component in the flue gas, accounting for over 74%. The concentration of greenhouse gases (CH_4 and CO_2 combined) was less than 1. The thermal plasma reactor gasifies the wastewater sludge from the petroleum industry into flue gases with slag as a byproduct. The CO richen flue gas can be enriched with hydrogen to produce syngas.

5. RECOMMENDATION

Further research should look into the effect of cathode diameter on plasma temperature.

REFERENCES

Agon, N. (2015). *Development and study of different numerical plasma jet models and experimental study of plasma gasification of waste.* Ghent University.

Ali, A. M., Abu-Hassan, M. A., Ibrahim, R. R. K., Zaini, M. A. A., Abdulkarim, B. I., Hussein, A. S., Su, S. M. and Mohd-Halim, M. I. (2017). Characterization of Petroleum Sludge from Refinery Industry Biological Wastewater Treatment Unit. *The International Journal of Engineering and Science (IJES), 6*(9), 61 - 65. doi: 10.9790/1813-0609016165

Ali, A. M., Abu Hassan, M. A. and Abdulkarim, B. I. (2016). Thermal Plasma: A Technology for Efficient Treatment of Industrial and Wastewater Sludge. *IOSR Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT), 10*(11), 63 - 75. doi: 10.9790/2402-1011046375

Ali, A. M., Abu Hassan, M. A., Ibrahim, R. R. K., Jalil, A. A., Mat Nayan, N. H., Abdulkarim, B. I. and Sabeen, A. H. (2019). Analysis of Solid residue and Flue Gas from Thermal Plasma Treatment of Petroleum Sludge. *Journal of Environmental Chemical Engineering, 7*(4), 103207. doi: https://doi.org/10.1016/j.jece.2019.103207

Barcza, N. (1986). The development of large-scale thermal-plasma systems. *J. S. Afr. Inst. Min. Metall., 86*(8), 317-333.

Bień, J., Celary, P., Morzyk, B., Sobik-Szołtysek, J. and Wystalska, K. (2013). Effect of Additives on Heavy Metal Immobilization During Vitrification of Tannery Sewage Sludge. *Environment Protection Engineering, 39*(2). doi: 10.5277/EPE130204

Celary, P. and Sobik-Szołtysek, J. (2014). Vitrification as an alternative to landfilling of tannery sewage sludge. *Waste Management, 34*(12), 2520-2527. doi: http://dx.doi.org/10.1016/j.wasman.2014.08.022

Cortez, R., Zaghloul, H. H., Stephenson, L. D., Smith, E. D., Wood, J. W. and Cahil, D. G. (1996). Laboratory scale thermal plasma arc vitrification studies of heavy metal-laden waste. *Journal of the Air & Waste Management Association, 46*(11), 1075-1080.

Cubas, A. L. V., Carasek, E., Debacher, N. A. and De-Souza, I. G. (2005). Development of a DC-Plasma Torch Constructed with Graphite Electrodes and an Integrated Nebulization System for Decomposition of CCl4. *J. Braz. Chem. Soc., 16*(3B), 531-534.

Cubas, A. L. V., Machado, M. D.-M., Machado, M. D.-M., Gross, F., Magnago, R. F., Moecke, E. H. S. and De-Souza, I. G. (2014). Inertization of Heavy Metals Present in Galvanic Sludge by DC Thermal Plasma. *Environmental science & technology, 48*(5), 2853-2861. doi: 10.1021/es404296x

Diya'uddeen, B. H., Wan-Daud, W. M. A. and Abdul-Aziz, A. R. (2011). Treatment technologies for petroleum refinery effluents: a review. *Process Safety and Environmental Protection, 89*(2), 95-105.

Heberlein, J. (2002). New approaches in thermal plasma technology. *Pure and Applied Chemistry, 74*(3), 327-335.

Heberlein, J. and Murphy, A. B. (2008). Topical review: Thermal plasma waste treatment. *Journal of Physics D: Applied Physics, 41*, 1-20. doi: 10.1088/0022-3727/41/5/053001

Khongkrapan, P., Thanompongchart, P., Tippayawong, N. and Kiatsiriroat, T. (2013). Fuel gas and char from pyrolysis of waste paper in a microwave plasma reactor. *International Journal of Energy And Environment, 4*(6), 969 - 974.

Kim, H. and Park, D. (2004). Characteristics of Fly Ash/Sludge Slags Vitrified by Thermal Plasma. *J. Ind. Eng. Chem., 10*(2), 234-238.

Kim, S. W., Park, H. S. and Kim, H. J. (2003). 100 kW steam plasma process for treatment of PCBs (polychlorinated biphenyls) waste. *Vacuum, 70*(1), 59-66. doi: http://dx.doi.org/10.1016/S0042-207X(02)00761-3

Kourti, I., Devaraj, A. R., Butos, A. G., Deegan, D., Boccaccini, A. R. and Cheeseman, C. R. (2011). Geopolymers prepared from DC plasma treated air pollution control (APC) residues glass: Properties and characterisation of the binder phase. *Journal of Hazardous Materials, 196*, 86-92. doi: http://dx.doi.org/10.1016/j.jhazmat.2011.08.081

Leal-Quirós, E. and Villafañe, C. R. (2007). An Assessment of the Power Generated With Plasma Processing of Sludge From Wastewater Treatment Plants. *IEEE Transactions On Plasma Science, 35*(6), 1622 - 1627.

Li, C., Lee, W., Huang, K., Fu, S. and Lai, Y. (2007). Vitrification of Chromium Electroplating Sludge. *Environmental science & technology, 41*(8), 2950-2956. doi: 10.1021/es062803d

Li, O. L.,Guo, Y., Chang, J. S., Urashima, K. and Saito, N. (2012). Treatment of Non-point Sources by a Thermal Plasma System Under DC Partial Transferred Mode. *International Journal of Plasma Environmental Science & Technology, 6*(1), 63 - 67.

Li, O. L., Guo, Y., Chang, J. S., Urashima, K. and Saito, N. (2015a). A new approach of nonpoint source pollution/stormwater sludge treatment by an integrated thermal plasma system. *International Journal of Environmental Science and Technology, 12*(5), 1769-1778. doi: 10.1007/s13762-014-0570-7

Li, O. L., Guo, Y., Chang, J.S., and Saito, N. (2015b). Thermal plasma treatment of stormwater sediments: comparison between DC nontransferred and partially transferred arc plasma. *Environ Technol, 36*(13), 1672-1679.

Mohai, I. and Szépvölgyi, J. (2005). Treatment of particulate metallurgical wastes in thermal plasmas. *Chemical Engineering and Processing, 44*, 225-229.

Mountouris, A., Voutsas, E. and Tassios, D. (2008). Plasma gasification of sewage sludge: Process development and energy optimization. *Energy Conversion and Management, 49*(8), 2264-2271. doi: http://dx.doi.org/10.1016/j.enconman.2008.01.025

Punčochář, M., Ruj, B. and Chatterj, P. K. (2012). Development of Process for Disposal of Plastic Waste Using Plasma Pyrolysis Technology and Option for Energy Recovery. *Procedia Engineering, 42*, 420-430. doi: http://dx.doi.org/10.1016/j.proeng.2012.07.433

Ramachandran, K. and Kikukawa, N. (2002). Thermal Plasma In-Flight Treatment of Electroplating Sludge. *IEEE Transactions On Plasma Science, 30*(1), 310-317.

Shie, J., Liau, Y., Lin, K. and Chang, C. (2014). *Thermal Treatment of Paper Sludge Using Torch Plasma.* Paper presented at the 2014 4th International Conference on Future Environment and Energy, IACSIT Press, Singapore.

Sobiecka, E. and Szymanski, L. (2014). Thermal plasma vitrification process as an effective technology for fly ash and chromium-rich sewage sludge utilization. *Journal of Chemical Technology & Biotechnology, 89*(7), 1115-1117. doi: 10.1002/jctb.4221

Szałatkiewicz, J., Szewczyk, R., Budny, E., Missala, T. and Winiarski, W. (2012). Determination of PID control parameters of plasmatron plasma reactor. *Journal of Applied Computer Science Methods, 4*(2), 31--39.

Szałatkiewicz, J., Szewczyk, R., Budny, E., Missala, T. and Winiarski, W. (2013). Construction Aspects of Plasma Based Technology for Waste of Electrical and Electronic Equipment (WEEE) Management in Urban Areas. *Procedia Engineering, 57*(Supplement C), 1100-1108. doi: https://doi.org/10.1016/j.proeng.2013.04.139

Tang, L. and Huang, H. (2005). Treatment of Waste Tyre Powder Using a High-frequency Capacitively Coupled Plasma Reactor. *Chinese Journal of Process Engineering, 5*(3), 295-300.

Tang, L., Huang, H., Zhao, Z., Wu, C. Z. and Chen, Y. (2003). Pyrolysis of Polypropylene in a Nitrogen Plasma Reactor. *Ind. Eng. Chem. Res., 42*, 1145-1150.

Tippayawong, N. and Khongkrapan, p. (2009). Development of a laboratory scale air plasma torch and its application to electronic waste treatment. *Int. J. Environ. Sci. Tech., 6*(3), 407-414.

Townsend, T. and Oehmig, W. (2014). *Development of a Bench-Scale Plasma Arc Vitrification Unit and the Exploration of Element Behavior in High Temperature Plasma Vitrification.* (PhD), University of Florida, Hinkley Center for Solid and Hazardous Waste Management. (Report # 81839)

Tu, W. A., Shie, J. L., Chang, C. Y., Chang, C. F., Lin, C. F., Yang, S. Y., Kuo, J. T., Shaw, D. G. and Lee, D. J. (2008). Pyrolysis of Rice Straw Using Radio-Frequency Plasma. *Energy & Fuels, 22*(1), 24-30. doi: 10.1021/ef7002848

Zhao, Z., Huang, H., Wu, C., Li, H. and Chen, Y. (2001). Biomass Pyrolysis in an Argon/Hydrogen Plasma Reactor. *Eng. Life Sci., 1*(5), 197 - 199.