

Plasma Gasification: From a Dirty City to a Heavenly Place and from Waste Solids to Clean Fuel

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Abstract

Plasma gasification is a technology which can process landfill waste to extract commodity recyclables and convert carbon-based materials into fuels. Utilizing this technology to convert municipal solid waste (MSW) to energy has great potential to operate more efficiently than other pyrolysis and combustion systems due to its high temperature, heat density, and nearly complete conversion of carbon-based materials to syngas, and non-organics to slag. Syngas is a simple fuel gas comprised of carbon monoxide and hydrogen that can be combusted directly or refined into higher-grade fuels and chemicals. Slag is a glass-like substance which is the cooled remains of the melted waste; it is tightly bound, safe and suitable for use as a construction material. Plasma torch technology has proven reliable at destroying hazardous waste and can help transform environmental liabilities into renewable energy assets. There is a plasma gasification plant in Utashinai, Japan. It is the largest plasma gasification plant in the world and was built by Hitachi Metals Ltd. using Westinghouse plasma corporation plasma gasification process. The plant takes up 300 tonnes per day of MSW as feedstock and produces 7.9MW of energy, of which 3.6MW is used by the plant and the rest is sent to a central processing grid which can be used to provide a part of the power required by the city or for any other constructive purpose. Based on the model of Japan's plasma gasification plant, in this paper an attempt has been made to offer a lasting environment friendly solution to Mumbai's twin problems of tonnes of daily waste generation and disposal, and recurrent power shortage.

Keywords: Plasma Gasification, Waste-to-Energy, Effective waste management

I. INTRODUCTION

According to the 2011 census the population of Mumbai, Maharashtra, India, is estimated to be about 12.4 million, which is an increase of about 4.7% from the last record of the population i.e. 11.9 million in 2001. The city, which is the capital of Maharashtra and the commercial capital of India, is the most populous city of the country and the fourth most populous city in the entire world.

Naturally, if the population is so large, the municipal waste generated is also large. According to 2011 census, every day, Mumbai generates around 7,500 MT of municipal solid waste. The rate of waste generation is also increasing due to the increasing population. Municipal Solid Waste (MSW) is dumped in the outskirts of the cities in low lying areas with no compliance of regulations. The dumped waste contains organic, inorganic and inert material like debris in mixed form. The garbage is sent to sanitary landfills for disposal but the amount of MSW is so high that these landfills cannot accommodate it. This results in the garbage being dumped for longer periods than should be and ultimately causes adverse effect on the environmental and human health.

As per the Development Planning Regulations prepared by the Brihanmumbai Municipal Corporation (BMC), the projected population in 2020 will be approximately 13,500,000 and hence the garbage generated will be 9,000 MT per day i.e. 20% more than the present quantity. But, the size of the dump yards and landfills will remain the same and even if they increase it wouldn't be proportional to the rate at which the MSW is generated. Hence, it is of utmost importance to consider safer options for MSW management. Hence, plasma gasification has been considered as a solution to this problem.

The principal advantages that a plasma offers to treatment processes are [1, 2]:

A. *High Energy Densities and High Temperatures, Characteristics Which Allow:*

- rapid heating and reactor start-up,
- high heat and reactant transfer rates,
- smaller installation size for a given waste throughput,
- melting of high temperature materials,
- high quench rates to obtain non-equilibrium compositions or metastable materials, and

B. Use of Electricity as the Energy Source, Resulting In:

- decoupling of the heat generation from the oxygen potential and the mass flow rate of the oxidant or air,
- control of the processing environment,
- more options for the process chemistry,
- lower off-gas flow rates and consequently lower gas cleaning costs,
- the possibility of producing saleable co-products.

II. MATERIALS AND METHODS

Gasification was the first industrial thermochemical process. It appeared at the end of the nineteenth century and was developed through the industrialization of Europe, mostly for the production of oil and gas from coal. In the 1970s and 1980s, the use of gasification for the production of synthetic fuels began. In the 1980s, the U.S., Europe and Japan also began the development of gasification for the treatment of wastes.

The use of gasification for MSW has been mostly applied in Japan, where their lack of space forced them to find alternatives to landfilling. As we will see further on, Japan has also the only commercial plasma arc facility that treats MSW, in Utashinai, operated by Hitachi metals and Alter NRG.

Thermal plasma, often called as the ‘fourth state of matter’, is the term given to gas that has been ionized. Ionized gas is a mixture of ions, electrons and neutral particles and hence, it is electrically charged. In nature, plasma is found in lightning and on the surface of the sun. Synthetically, ionization of gases is not possible at normal temperatures, it only occurs at very high temperatures (>5000°C). Plasma torches are used to ionize gases and the high temperatures reached during this process are utilized for the gasification process.

A. Composition of Solid Waste of Mumbai:

Mumbai, the commercial and financial capital of India is spread over an area of around 437.71 sq km and houses more than 12 million people. Compared to other metropolitan cities in India as well as in Maharashtra, the amount of MSW generation is the highest in Mumbai and the city alone generates about 7,500 TPD. It comprises of various types of wastes including biodegradable waste, plastics, leather, glass, metals, etc. The exact composition of municipal waste generated in Mumbai as per the survey carried out NEERI CPCB(2005) is given in figure1.

Composition of solid waste of Mumbai

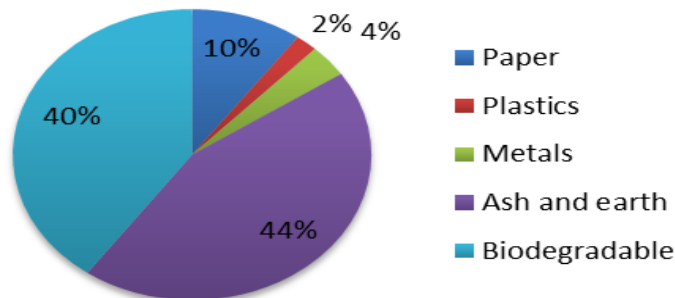


Fig. 1: Composition of Solid waste of Mumbai

B. Plasma Gasification Process:

Plasma gasification is a multi-stage process with is shown in figure 2.

The process starts with feed inputs – ranging from waste to coal to plant matter, and can include hazardous wastes. The first step is to process the feed stock to make it uniform and dry, and have the valuable recyclables sorted out i.e. sorting and size reduction (crushing) of the feed it carried out. Drying is done only in case of wet feed or sludge.

The MSW is then sent to a thermal plasma furnace. Plasma torches are used at the bottom of the gasifier to provide sufficient heat for the gasification to take place. The air flow inside the gasifier is controlled. A bed coke is created within the reactor using metallurgical coke (met coke) to absorb and retain the heat energy from the plasma torches and provide a ‘skeleton’ that supports the MSW feed as it descends the gasification reactor and gets converted to gas and liquid slag. As the mix of waste and met coke is going down through the gasifier, the waste will start gasifying whereas the met coke will remain solid. The bed coke will slowly gasify but will remain at the bottom. The bed waste will lie on top of it. The only materials that will escape the bed coke are the slag and melted metals. The met coke has a very good structural integrity and hence is able to support the weight of the waste on to it. The met coke is fed at the same time as the MSW and is vital for the operation of the gasifier. Powdered limestone is added to the coke injection to eliminate the risk of fire and explosions. It also helps to reduce HCl emissions from the gasifier. Another importance of limestone is that it reacts in this region (i.e. the gasifier) and helps to maintain a suitable composition for the production of a vitreous material or slag that can be tapped off in molten form. Sometimes, LPG burner is installed to raise the initial temperature and add heat when the heating value of solid waste is not enough.

During the gasification process, the temperature inside the gasifier is as high as 5000°C- 7000°C. At such high temperature the inorganic matter is converted into liquid slag while carbon based complex molecules breakdown into simple gases like hydrogen and carbon monoxide gas which make up the syngas. The gasifier works at a slightly negative pressure to avoid leaking of gas. The syngas that leaves the gasifier has a temperature between 1000°C and 1200°C. It is passed through a heat exchanger where the heat from the gas is recovered and used to generate steam from water. This steam is used to generate electricity using steam turbines. The cooled syngas is cleaned up and purified and can be used to produce fuels.

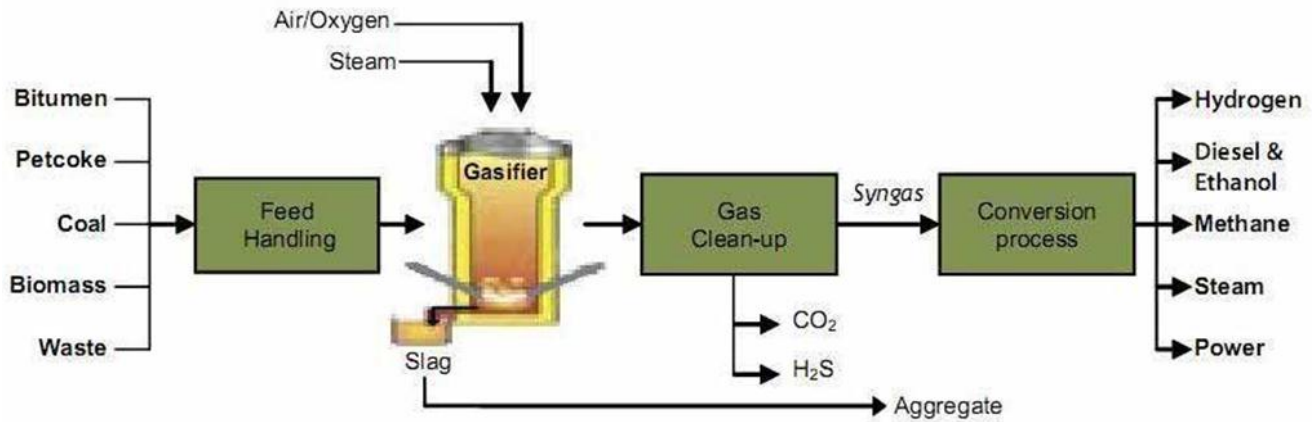


Fig. 2: Schematic diagram of the overall gasification process for waste treatment using thermal plasma

The solid by-product from the gasification process is called slag. If slag is air-cooled, it forms black, glassy rocks that look and feel like obsidian, which can be used in concrete or asphalt. Molten slag can be funnelled into brick or paving stone moulds and then air cool into ready-to-use construction material. If air is blow compressed through a stream of this molten material, rock wool is obtained.

C. Plasma Torch:

Arc plasma torches are the primary components of various industrial thermal plasma processes involving plasma spraying, metal cutting and welding, metal melting and remelting, waste treatment and gas production. They are relatively simple devices whose operation implies intricate thermal, chemical, electrical, and fluid dynamics phenomena. The modeling of DC arc plasma torches is extremely challenging because the plasma flow is highly nonlinear, presents strong property gradients, is characterized by a wide range of time and length scales, and often includes chemical and thermodynamic non-equilibrium effects, especially near its boundaries.

DC arc plasma torches are of two types:

- Transferred arc torches
- Non-transferred arc torches.

For our process we use non transferred DC plasma torches. Figure 3 shows a typical non transferred plasma torch.

Most DC arc torches have three main components: The cathode, the plasma-forming gas injection stage, and the anode. The anode usually also acts as arc constrictor in the non-transferred arc torches. Inside the torch, the working gas flows around the cathode and through a constricting tube or nozzle. The plasma is usually initiated by a high voltage pulse which creates a conductive path for an electric arc to form between the cathode and anode (the torch nozzle in non-transferred arc torches). The electric heating produced by the arc causes the gas to reach very high temperatures (e.g. > 10000 K), thus to dissociate and ionize. The cold gas around the surface of the water cooled nozzle or constrictor tube, being electrically non-conductive, constricts the plasma, raising its temperature and velocity. Most of the commercial plasma spray torches operate at atmospheric pressure with electric power levels ranging between 10 and 100 kW, arc currents between 250 and 1000 A, arc voltages between 30 and 100 V, and flow rates between 20 and 150 slpm (standard liters per minute). Common gases used in thermal plasma processing are Ar, He, H₂, N₂, O₂, and mixtures of these. Non-transferred arc torches are typically used in applications that rely on the formation of a plasma jet with moderate to very high velocity and, its use as a heat source, high temperature processing medium or source of specific reactive species, such as plasma spraying and powder synthesis.

Several major companies like Westinghouse plasma corporation, Europlasma, Tetratics, Pheonix manufacture plasma torches. In this process, we have considered a Westinghouse Plasma Corporation MARC 3A plasma torch operating at the electrical ranges based on the configurations given below:

Rated minimum power (kW)	80
Rated maximum power (kW)	300
Air flow (kg/hr)	42
Thermal efficiency	70%
Maximum operating current	400ADC
Maximum operating voltage	860ADC

The torch has a diameter of about 3.5 inches and the typical length is 32.5 inches.

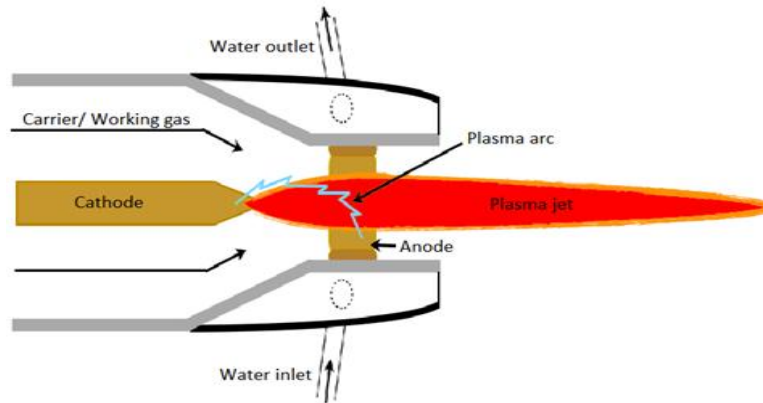
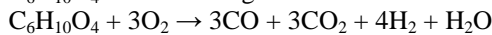


Fig. 3: Non transferred DC torch

III. ENERGY AND MATERIAL BALANCES FOR 200 TPD SCALE THERMAL PLASMA GASIFICATION PLANT FOR MSW TREATMENT

The calorific value of the solid waste of Mumbai from reference [] is about 9.022 MJ/kg or 2.505 kWh/kg. Therefore, a ton of waste contains 9022MJ or 2505 kWh of chemical energy.

On the basis of chemical analysis, the average composition of combustible materials in MSW can be expressed by the formula $C_6H_{10}O_4$. The overall gasification reaction of solid waste using thermal plasma (assuming no heat loss) is given as:

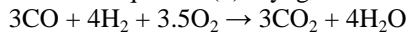


$$\Delta H = -1300 \text{ kWh/ton} \quad (1)$$

The main gasification reactions taking place are: (Krigmont, 1999)

- 1) $C + O_2 \rightarrow CO_2 -393 \text{ kJ/mol}$ (exothermic)
- 2) $C + H_2O \rightarrow CO + H_2 +131 \text{ kJ/mol}$ (endothermic)
- 3) $C + CO_2 \rightarrow 2.CO +172 \text{ kJ/mol}$ (endothermic)
- 4) $C + 2H_2 \rightarrow CH_4 -74 \text{ kJ/mol}$ (exothermic)
- 5) $CO + H_2O \rightarrow CO_2+ H_2 -41 \text{ kJ/mol}$ (exothermic)
- 6) $CO + 3H_2 \rightarrow CH_4 + H_2O -205 \text{ kJ/mol}$ (exothermic)

The principal product of plasma gasification of MSW is a low to medium calorific value syngas composed of CO and H₂ as shown in equation (7). Syngas combusts according to the following equations:



$$\Delta H = -1500 \text{ kWh/ton} \quad (8)$$

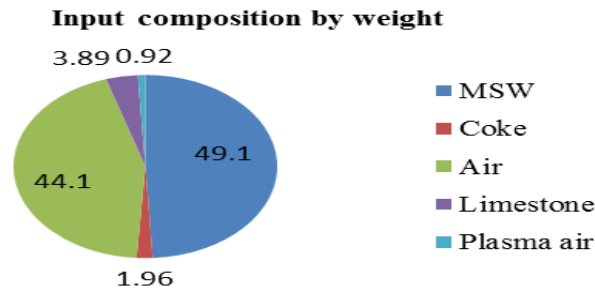


Fig. 4: Input composition by weight to a WPC reactor

The typical syngas composition and contaminants present in it are given in the figure (5).

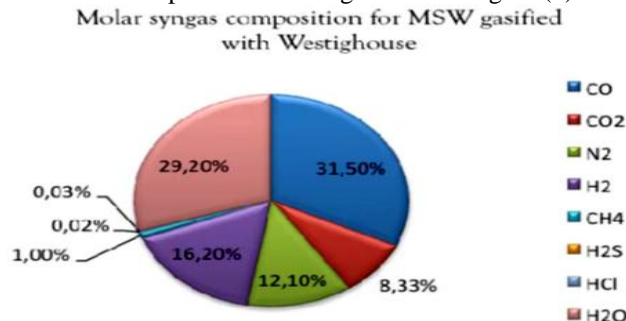


Fig. 5: Molar composition of the syngas

Table- 1: Material Balance of the Plasma Furnace

Components	In(kgs/day)	Out(kgs/day)
Feed (Mixture of MSW, coke, limestone, air and plasma air)	408163 (MSW=200000 Coke=8000 Limestone=16244 Air=179591.8 Plasma air=6227)	
Syngas		204081.5 (Since biodegradables and paper waste come out to be 50% of the feed)
Slag		204081.5

The energy balance of the plasma furnace is given in table 2. Energy can be recovered from the sensible heat of the syngas.

Due to thermal losses, we can assume that the syngas carries about 90% of the energy brought by the solid fuel and the coke. An estimated 80% of this energy is in the form of chemical energy in the syngas and 20% is thermal energy, in the form of sensible heat. The thermal energy is not recovered in our case. Hence, for the above calculations of one ton of MSW processed, the solid feed chemical energy (MSW + coke) is 2683.53 kWh, so the approximate energy available in the syngas is:

$$0.90 * 0.80 * 2683.53 = 1932.14 \text{ kWh/ton}$$

Table- 2: Energy Balance for the Plasma Furnace

Components	Input(kWh/ton)	Output(kWh/ton)
MSW	2505	
Coke (LHV= 32.8MJ/kg)	$32.8 * 10^{(6)} * 0.0196 * 2.777 * 10^{(-7)} * 10^{(3)} = 178.53$	
Plasma Torches (6 torches consuming 300kW each & efficiency 70% With the feed flowing at a rate of 10ton/hr)	$6*300*0.7/10 = 126$	
Syngas (Assuming 10% losses and out of the remaining 80% gets converted to chemical energy and 20% to thermal energy which is not recovered)		$0.9 * 0.8 * 2683.53 = 1932.14$
Slag		Energy from slag is not recovered since it has to be rapidly cooled so that it is passed through the glass transition temperature to form vitreous material.

A. Energy Production:

Electricity is produced in one of three ways; through the use of boilers and steam turbines, gas engines, or gas turbines. Engines and turbines require very clean gasses. Straight combustion to fire a boiler can use dirtier gasses and has the lowest cost of all the options. Steam turbine systems may generate 500 - 600kwh per ton of MSW. Gas turbines in a combined cycle may generate 1000-1200kwh per ton of MSW.

Integrated Gasification Combined Cycle (IGCC) is considered the state of the art and most efficient means to generate power from carbon resources and is the model used for modern clean coal power plants. In IGCC the syngas is combusted in an advanced turbine (similar to a jet engine) such as those manufactured by GE. The turbine produces electricity, and additionally the hot turbine exhaust is captured in a heat recovery steam generator (HRSG) to produce electricity from a steam turbine. The combination of a steam turbine with the gas turbine is the combined cycle. Gas turbines are very large pieces of equipment that produce from 40MW to over 200MW of power.

For MSW gasification, the plant needs to handle a minimum of 750 tons per day to be able to utilize IGCC. Smaller systems could utilize banks of engines that operate from 1MW-4MW each, such as the engines that can be run in combined cycle mode. The simplest systems use boilers and steam turbines. Steam turbines range in size from the smallest at just a few KW to the very largest at 500MW and above such as those used for nuclear power plants and large coal power stations.

IV. RESULTS AND CONCLUSION

Plasma gasification of waste prevents many environmental effects arising due to land-filling and incineration of waste.

A. Plasma Gasification over Landfills:

Gasification is superior to landfilling MSW for a number of reasons. Landfills are toxic to the environment due to the production of toxic liquid leachate and methane gases. Decomposition and chemical reactions among the waste produces liquids that leach out and may contaminate ground water. Decomposition of organic matter produces methane, which is a potent greenhouse gas. Other chemicals may be produced that toxify the air around a landfill and may be harmful to neighbours. The EPA has a lengthy protocol of airborne and liquid chemicals that must be contained and monitored into eternity for every landfill.

Modern landfills must be constructed with liners and leachate drains. These facilities are becoming increasingly expensive as more environmental regulations come into existence. When landfills are closed, they must be capped and monitored indefinitely. Despite expensive management strategies, the only good solution for landfills is to avoid them. Plasma gasification is an ideal treatment strategy to divert waste from landfills and create beneficial uses for the material by maximizing recycling of valuables and cleanly use the rest for its fuel value. The carbon impact of plasma gasification is significantly lower than other waste treatment methods and is rated to have a negative carbon impact compared to allowing methane to form in landfills.

B. Plasma Gasification over Incineration:

Gasification is superior to incineration, and offers dramatic improvement in both its environmental impact as well as its energy performance. Incineration has long had problems with the formation of dioxins and other critical pollutants. Incinerators are high-temperature burners that use the heat generated from the fire to run a boiler and steam turbine to produce electricity, very similar to conventional coal-fired power plants. During combustion, complex chemical reactions take place that bind oxygen to various molecules and form pollutants such as sulfur oxides, nitrogen oxides and dioxins. These pollutants pass through the smokestack unless exhaust scrubbers are put in place to clean the gases. Gasification by contrast is a low oxygen process, and fewer oxides are formed. The scrubbers for gasification are placed in line and are critical to the formation of clean gas. Scrubbers in a gasification system are integral to the operation of the system regardless of the regulatory environment. For combustion systems, the smokestack scrubbers offer no operational benefit and are put in place primarily to meet legal requirements. The ash from incinerators is also highly toxic and is disposed of in landfills, while the slag from plasma gasification is safe because all of the ash is melted and reforms in tightly bound molecular structure.

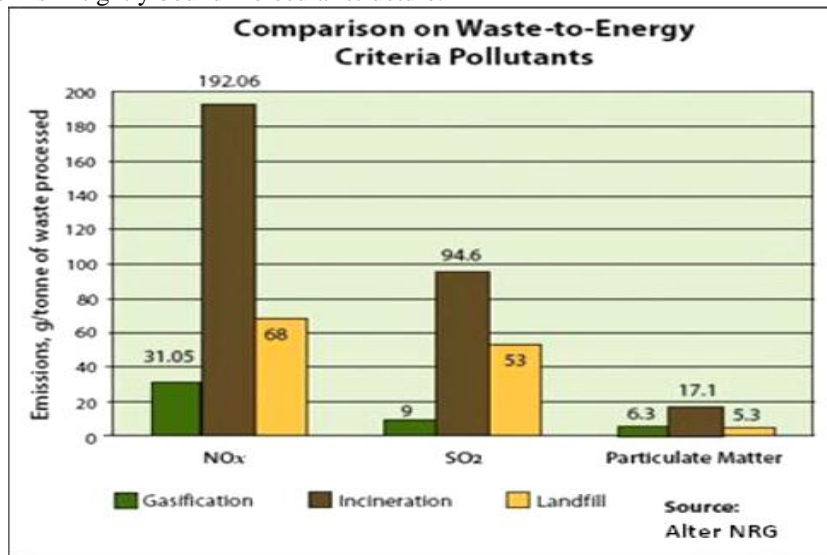


Fig. 6: Comparison on Waste-to-Energy Criteria Pollutants

Table- 3: Electricity production by different processes

PROCESS	ELECTRICITY to GRID (kWh/ton)
Plasma Arc Gasification	816
Conventional Gasification -Fixed / Fluidized Bed Technologies	685
Pyrolysis & Gasification - Thermoselect Technology	685
Pyrolysis - Mitsui R21 Technology	571
Incineration - Mass Burn Technology	544

Also gasification produces maximum electricity as compared to other processes which can be seen in table 3.

In this paper, I have shown the energy and material balances for a plasma gasification model of 200 TPD, based on the case study of Utashinai, Japan model.

By this process, there is not only effective management of the municipal waste but also gives useful by products like slag along with production of clean electricity. This model can be scaled up to process the waste of Mumbai on a larger scale.

REFERENCES

- [1] Caroline Ducharme, Technical and economic analysis of Plasma-assisted Waste-to-Energy processes Department of Earth and Environmental Engineering Fu Foundation of Engineering and Applied Science Columbia University: September 2010
- [2] Youngchul Byun, Moohyun Cho, Soon-Mo Hwang and Jaewoo Chung, Thermal Plasma Gasification of Municipal Solid Waste (MSW), Chung et. Al, licensee InTech: 2012.
- [3] Joachim Heberlein and Anthony B Murphy, Topical Review Thermal plasma waste treatment Journal Of Physics D: Applied Physics, 41 (2008) 053001
- [4] Plasma torches by Westinghouse Plasma Corporation, Westinghouse Plasma Corporation, a division of AlterNRG.
- [5] Tetronics Non-Transferred DC Plasma Arc Torches: Version 1, 21012013
- [6] A. Mountouris, E. Voutsas, D. Tassios, Plasma gasification of sewage sludge: Process development and energy optimization, Energy Conversion and Management, Volume 49, Issue 8, August 2008, pp. 2264–2271
- [7] Ed Dodge, Cornell University-Johnson Graduate School of Management, Queens University School of Business. Plasma Gasification: Clean Renewable Fuel Through Vaporization Of Waste, July,2008
- [8] J. P. Trelles, C. Chazelas, A. Vardelle and J. V. R. Heberlein, Arc Plasma Torch Modeling
- [9] Louis Circeo, Luciano Bardari, Plasma Gasification: A Significant Global Waste-to-Energy Opportunity, Symposium Venice 2012
- [10] How Plasma Converters Work by Jonathan Strickland
- [11] Martin GmbH, Review of the State-of-the-Art Waste-to-Energy Technologies Stage-two: Case Studies, January, 2013