

Treatment of organic waste using thermal plasma pyrolysis technology

H. Huang^{a,*}, L. Tang^b

^a Department of Environmental Engineering, Guangdong University of Technology, Zhonghuanxi Road, Guangzhou 510006, PR China

^b Department of Civil Engineering, Guangzhou University, Waihuanxi Road, Guangzhou 510006, PR China

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Abstract

This paper outlines the principles of thermal plasma pyrolysis processes and discusses recent research activities about organic waste treatment using thermal plasma pyrolysis technology. Different kinds of organic wastes, varying from plastic and used tires to agricultural residue and medical waste, have been subjected to thermal plasma pyrolysis tests in laboratory and pilot scale projects. Plasma pyrolysis of organic waste usually gives two product streams: a combustible gas having a calorific value in the range of 4–9 MJ/Nm³ and a carbonaceous residue. Pyrolysis conditions as well as some technical measures such as the quenching process and steam reforming have significant influences on the properties of these pyrolysis products. Research results indicated that thermal plasma pyrolysis may be a useful way of waste management for energy and material recovery.

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1. Introduction

Waste management is an important issue in both developed and developing countries nowadays [1–5]. Organic wastes, such as used rubber [6,7] and plastic [8–10] are among the waste materials that represent problematic wastes on one hand and valuable potential as secondary raw materials on the other hand. To alleviate part of our energy crisis and environmental degradation, it has become imperative to make use of appropriate technologies for recovery of resources from non-conventional sources like organic waste.

As the general trend is to limit landfill sites, the disposal alternatives left for organic waste will be incineration and recycling. Incineration may utilize the energy content of organic waste but is associated with the generation of SO₂, NO_x and other hazardous emissions. The problems that occurred in the earlier recycling technologies based on pyrolysis and gasification are such as low gas productivity and the wide spectrum of products. These problems are difficult to overcome due to only limited control of the

product composition in pyrolysis and gasification processes.

Thermal plasma technology has been under active development for a long time [11]. The technology is now well established in metallurgical processing, materials synthesis etc. [12–14]. The extremely high temperatures generated by plasma torches have spurred development of their application to waste processing, as they are capable of significantly decreasing the waste volume to a non-leachable residue. By far the most important application of thermal plasma waste treatment is focused on the destruction of hazardous wastes [15–17] rather than recycling because of economic issues. Nevertheless, in recent years, the interest in energy and resource recovery from waste has grown significantly, and substantial research about the use of plasmas in organic waste treatment has been conducted. A review of the progress is presented in this paper. Because the progress of plasma pyrolysis technology is heavily dependent upon the availability of appropriate plasma generating devices, a brief discussion is also included on this topic.

2. Basic plasma properties

Plasma is considered by many to be the fourth state of matter, following the more familiar states of solid, liquid

* Corresponding author. Fax: +86 2039322547.

E-mail addresses: huanght@gdut.edu.cn, ht.huang@163.com (H. Huang), tanglan@gzhu.edu.cn (L. Tang).

Table 1
Classification of plasmas

Plasma	State	Example
<i>High temperature plasma</i> High temperature plasma (Equilibrium plasma)	$T_e = T_i = T_h, T_p = 10^6 \text{ K} - 10^8 \text{ K}$ $n_e \geq 10^{20} \text{ m}^{-3}$	Laser fusion plasma
<i>Low temperature plasma</i> Thermal plasma (Quasi-equilibrium plasma)	$T_e \approx T_i \approx T_h, T_p = 2 \times 10^3 \text{ K} - 3 \times 10^4 \text{ K}$ $n_e \geq 10^{20} \text{ m}^{-3}$	Arc plasma; atmospheric RF discharge
Non-thermal plasma (Non-equilibrium plasma)	$T_e \gg T_h \approx 3 \times 10^2 \text{ K} - 4 \times 10^2 \text{ K}$ $n_e \approx 10^{10} \text{ m}^{-3}$	Corona discharge

Note: T_e = electron temperature; T_i = ion temperature; T_h = Neutral temperature; T_p = Plasma temperature; n_e = Electron density.

and gas. Addition of sufficient energy to a gas converts the gas into plasma. In other words, plasma is an ionized gas resulting from an electrical discharge, for instance. We can distinguish two main groups of laboratory plasmas, i.e. the high temperature or fusion plasmas and the so called low temperature plasmas or gas discharges. A typical classification of different kinds of plasmas is given in Table 1. High temperature plasma implies that all species (electrons, ions and neutral species) are in a thermal equilibrium state. Low temperature plasma is divided into thermal plasma, also called quasi-equilibrium plasma, which is in a local thermal equilibrium (LTE) state, and non-thermal plasma, also called non-equilibrium plasma or cold plasma. The state parameters of each type are listed in Table 1. The subject of the present review paper is limited to thermal plasma and its application in waste treatment.

3. Thermal plasma generators (torches)

Thermal plasma generation can be achieved using a direct current (DC) or an alternating current (AC) electrical discharge or using a radio frequency (RF) induction or a microwave (MW) discharge. A DC arc discharge provides a high energy density and high temperature region between two electrodes and, in the presence of a sufficiently high gas flow, the plasma extends beyond one of the electrodes in the form of a plasma jet. The arc plasma generators can be divided into non-transferred arc torch and transferred arc torch. In a non-transferred arc torch, the two electrodes do not participate in the processing and have the sole function of plasma generation. In a transferred arc reactor, the substance to be processed is placed in an electrically grounded metallic vessel and acts as the anode, hence the reacting material should be an electrically conductive material. Transferred arc torches have been used widely in metallurgical processing. Arc torches and electrodes are usually water cooled, and the average lifetime of the electrodes ranges between 200 and 500 h of operation under oxidative conditions. DC arc plasma torches are commonly available at power levels up to 1.5 MW. Scale up is possible to 6 MW [18].

RF plasma torches utilize inductive or capacitive coupling to transfer electromagnetic energy from the RF

power source to the plasma working gas. They are very compact and deliver extraordinarily high input energy per unit volume. Unlike DC arc plasma torches, there are no locally high temperature arcs, no moving parts and no parts subject to wear. RF current and microwaves can be transferred through insulators, so the use of external electrodes is possible. In this way, the electrodes are not exposed to the severe conditions of thermal plasmas and, therefore, have a very long lifetime. RF plasma generators are commonly available at power levels of 100 kW. Scale up has been demonstrated to the 1 MW range [18].

Many thermal plasma processes have used DC plasma generators due to the stable arcs, but this kind of plasma generator requires expensive electronics and controls and the plasma plume is very narrow. RF inductively coupled plasma torches are being increasingly considered for a wide range of applications in the area of materials processing. Generally speaking, a RF plasma can generate a very diffuse plume, and the design of external electrodes favors the injection of feedstock material directly into or through the plasma region. However, RF plasma systems often utilize oscillator electronics, which have inherently low efficiencies.

The characteristics of thermal plasma torches have been studied extensively [19,20]. In a DC arc plasma, the temperature in the core of the plasma plume can be greater than 30 000 K, whereas in the marginal zones, the temperature decreases rapidly and the average operating temperature can be as high as 5000 K. In a RF plasma jet, the temperature at the central channel can reach up to 6000 K. A comparison of the main features of different plasma processes for waste treatment is given in Table 2.

4. Outline of thermal plasma pyrolysis of organic waste

Thermal plasma pyrolysis can be described as the process of reacting a carbonaceous solid with limited amounts of oxygen at high temperature to produce gas and solid products. In the highly reactive plasma zone, there is a large fraction of electrons, ions and excited molecules together with the high energy radiation. When carbonaceous particles are injected into a plasma, they are heated very rapidly by the plasma; and the volatile matter is

Table 2
Comparison of different plasma processes for waste treatment

Item	DC arc plasma	RF plasma
Temperature	5000–10000 K	3000–8000 K
Electrode erosion	Yes, (1000–3000 h lifetime in inert gas, 200–500 h lifetime in oxidative gas)	No
Cooling of plasma generator and reactor	Required	Required
Plasma ignition	Easy	Difficult
Plasma volume	Small	Medium
Gas velocity	High	High
Solid feeding position	Downstream of plasma	Upstream of plasma
Influence of solid feeding on plasma stability	No	Yes
Efficiency of power supply devices	60–90%	40–70%

released and cracked giving rise to hydrogen and light hydrocarbons such as methane and acetylene. Approximately four stages can be distinguished in the thermal plasma pyrolysis process:

- 1) A very fast heating of the particles as a result of their heat exchange with the plasma jet.
- 2) An explosive liberation of volatile matter from the particles.
- 3) A very quick gasification of the homogeneous phase and rapid heat and mass exchange.
- 4) Further gasification of char particles with various gaseous components.

Stage 3 could be replaced by quench technology in order to achieve certain technical purposes such as monomer recovery. Addition of water/steam could be effectively used in Stage 4 to promote syngas (H_2 and CO) production.

High temperature combined with the high heating rate of the plasma results in the destruction of organic waste, giving rise to a gas and a solid residue with varied properties depending on the feed characteristics and operating conditions. Plasma pyrolysis methods have previously been used in the production of carbon black [21] and coal gasification [22–24].

5. General conclusions from the results of important research examples on plasma pyrolysis

In order to exploit plasma pyrolysis as a potential technology for energy and raw materials recovery from organic waste, several laboratory and pilot scale projects have been undertaken in different countries [25–34]. Brief descriptions of a few such research activities are given in Table 3. The laboratory set up in these studies employed mostly entrained flow reactors; while in pilot scale projects, plasma fluidized or spouted bed reactors have been used. Various kinds of organic wastes have been tested such as used tires, polypropylene, polyethylene, agricultural residue etc.

The distribution of gas and solid product from plasma pyrolysis depends on the operating conditions such as plasma input power. The amount of gas product can reach up to 70–80% of the feed. For comparison, the gaseous product generated by conventional pyrolysis of waste tires is only 10–20% for slow pyrolysis [35] and 30–50% for rapid pyrolysis [36]. On the basis of the results of different researchers, the important operating parameters of thermal plasma pyrolysis are discussed below.

5.1. Operating power

The effect of operating power on plasma pyrolysis products is relatively well understood [26,29]. As the operating power is increased, the energy density and plasma discharge zone are increased. The longer plasma discharge zone results in longer residence time for particles in the high temperature zone, which, in turn, increases the probability of primary radical formation and gas yield.

Georgiev and Mihailov [37] developed a method for preliminary estimation of the energy in plasma pyrolysis systems. Their results indicated that specific energy consumption sharply increased above a certain temperature point, since with the increase of input power, the maximum temperature achieved in the discharge zone increased only slightly because of increased loss of the discharge power as radiation.

Tang et al. [29] performed experiments to compare the power consumption and increment of gas product at different conditions and suggested that excessive increase of input power was expected to have no significant meaning because, in the range of the parameters studied, the gaseous product composition of plasma pyrolysis is mainly controlled by the C/H ratio of the different materials. A suitable input power level should be chosen for a particular plasma pyrolysis process in order to obtain reasonable product yield using minimum specific power consumption.

5.2. Powder size

Solid conversion and final product formation take place in very short times due to the high enthalpy of the plasma. For example, experiments have been performed to investigate the gas composition and conversion at different sampling positions of a plasma reactor [29]. A very fast conversion in the first three sampling positions of the reactor was observed, corresponding to a residence time on the order of milliseconds. In other sampling locations, no further changes of conversion or composition of the gas product were observed. This phenomenon was also observed by other researchers [38,39].

The laboratory experimental set ups in these studies were entrained flow reactors. Because of the very short residence time of the particles, the rate of heat exchange of the particles with the plasma jet and the volatile disengagement from the particles (Stages 1 and 2) may themselves exert a

Table 3
Recent laboratory experiments on thermal plasma pyrolysis

Type of plasma	Reactor type/solid feeding mode	Feedstock tested	Investigator
Induction coupled plasma	The powder was carried in a flow of argon gas and injected into the center of the plasma	PP, PE	R.R. Guddeti [26,27]
DC plasma	A turntable type and a fluidized type powder feeder were used for injecting tire powder into the plasma	Used tires	J.S. Chang [28]
DC plasma	Powders from a screw feeder were injected using carrier gas into the plasma jet zone	PP, Used tires	L. Tang [29] H. Huang [30]
DC plasma	Plasma fluidized bed reactor; particles were added in the plasma or directly into the hot region of fluidized bed	Medical waste	S.K. Nema [31]
DC plasma	Powders from a screw feeder were injected using carrier gas into the plasma jet zone	Agricultural residue	Z. Zhao [32]
DC plasma	Plasma spouted bed reactor; particles were added directly into the hot region of the spouted bed	Municipal solid waste	R.W. Beck Inc.[33]
Microwave plasma	Coal was put in the middle of reactor before the plasma was generated	Coal	O. Kamei [34]

certain influence on the conversion. Feed materials were usually ground to small powders for the purpose of increasing the surface area and the total conversion to the gaseous product. In the plasma reactor, the particle speed depends on both the plasma jet speed and the distance to which the powders are injected into the plasma jet. The particle temperature is a function of the plasma enthalpy and of the residence time in the plasma jet. Besides, the speed and the temperature of the particles are influenced by their dimensions, specific heat capacity and density. A small particle size and a high heating rate are preferred for a higher conversion to gaseous product.

5.3. Quench process

Thermal plasma pyrolysis can also be used as a depolymerization process for monomer recovery from polymer waste when combined with a quench process. In plasma pyrolysis Stage 3, complex homogeneous reactions will take place after depolymerization. In order to preserve monomer molecules in the low temperature gas, a quenching process is needed to avoid further dissociation of the monomer molecules. Guddeti et al. [26] reported that using an induction coupled plasma (ICP) reactor combined with rapid quenching (1000 k/s), plasma plate power being in

the range of 10–20 kVA, waste PP can be depolymerized into propylene. The process is characterized by a high heating rate of the feed powder and rapid quenching of the product vapor to terminate the secondary conversion of the product. The conversion of PP to gas product is about 78%, and the main component of the gas product is propylene (see Table 4). The product of similar material treated by DC thermal plasma without a quench process is also listed in Table 4 for comparison. The conversion in the DC thermal plasma without quench process seems more complete than the reaction in the ICP because the high molecular weight volatiles had been decomposed almost completely into low molecular weight compounds such as H₂ and CH₄.

In ICP pyrolysis of PE, the gaseous products obtained were mostly mixtures of propylene and ethylene, together with smaller amounts of other hydrocarbons as listed in Table 4. Over the range of conditions investigated by Guddeti et al. [27], ethylene concentration ranged from 2.5% to 24%, propylene concentration ranged from 52% to 92% and the amount of solid residue collected ranged from 15% to 50% by weight of the total polymeric powder fed into the reactor. The amount of propylene was much higher than expected and was believed to be due to the β scission reaction mechanism occurring at the high temper-

Table 4
Product distribution with and without quench process

With quench process (Ref. [27])		With quench process (Ref. [26])		Without quench process (Ref. [29])	
Material: PE		Material: PP		Material: PP	
Product	Distribution (vol.% Ar free basis)	Product	Distribution (vol.% Ar free basis)	Product	Distribution (vol.% N ₂ -free basis)
Propylene	53.39	Propylene	93.7	Hydrogen	62.0
Ethylene	22.24	Ethylene	1.7	Acetylene	21.4
Methane	5.62	Methane	2.6	Methane	8.0
Acetylene	5.70	Butanes and butenes	1.3	C _n H _m and unknown	6.8
1,3-Butadiene	3.65				
Solid conversion	~50	Solid conversion	~78	Solid conversion	~94

Table 5
Product distribution from thermal plasma pyrolysis of PP with and without steam injection (Ref. [29])

Product	Concentration (vol.%)	
	Without steam injection	With steam injection
H ₂	14.99	27.06
CO	0.83	13.33
C ₂ H ₂	4.96	3.87
CH ₄	1.58	1.45
C ₂ H ₄	1.07	0.57
C ₂ H ₆	0.07	0.02
N ₂	71.83	49.02
C _n H _m + Unknown	4.17	4.37
Solid conversion	94%	96%
Gas yield	885 ml/g	2167 ml/g

atures. Hence, additional experiments involving variations of the residence time of the polymeric powder in the plasma zone should be conducted to obtain higher yields of monomer in the product gas stream. In addition, more work is required to investigate various types of quenching systems.

5.4. Steam reforming

The term “reforming” was originally used to describe the thermal and catalytic conversion of a petroleum fraction to a more volatile product of higher octane number and represented the total effect of many simultaneous reactions such as cracking, dehydrogenation and isomerization. Reforming also refers to the conversion of hydrocarbon gases and vaporised organic compounds to hydrogen containing gases such as synthesis gas, a mixture of carbon monoxide and hydrogen.

Experimental data listed in Table 5 show that using steam reforming, synthesis gas can be produced from waste polymer by thermal plasma pyrolysis. An essentially large volume of CO is generated under the water/steam plasma than under nitrogen or argon plasma, and at the same time, H₂ concentration and total gas yield are increased significantly. Beside reactions of the gaseous hydrocarbon and steam, the reaction between carbon and steam is believed to play an important role in the process according to the reaction: $C + H_2O \rightarrow CO + H_2$

6. Product characteristics

6.1. Gas

Typical distributions of thermal plasma pyrolysis gases obtained in different experiments are given in Table 6. Large quantities of combustible gases, such as H₂, CO, C₂H₂, CH₄, and C₂H₄, were produced during the pyrolysis processes. The concentrations of each component can vary considerably according to the feed characteristics and pyrolysis process parameters. Pollutant gases, such as SO₂ and NO_x are only found in low concentrations [40]. The combustion heat value of the gas product is in the range of 4–9 MJ/Nm³, so it can be used directly as a fuel in various energy applications such as direct firing in boilers, gas turbines or gas engines.

When steam reforming is incorporated in the plasma pyrolysis processes, the product gas may be utilized in syngas applications. It is known that synthesis gas having different H₂/CO molar ratios is suitable for different applications. For example, synthesis gas having a high H₂/CO molar ratio is desirable for producing hydrogen for ammonia synthesis. This ratio is increased further during the water–gas shift reaction for the removal of CO.

When product quenching is adopted as in Refs. [26,27], the gaseous products from plasma pyrolysis of polypropylene contained 94% propylene and small percentages of methane, ethylene etc. on an Ar free basis, and then, the propylene monomer can be obtained and recycled.

6.2. Char

Depending on the plasma pyrolysis conditions, the char fraction contains inorganic materials ashed to varying compounds, any unconverted solid additives such as carbon black filler in tires and carbonaceous residues formed from thermal decomposition of the organic components, and even carbon nano-particles produced in the gas phase secondary reactions [26].

Heating values of the chars obtained from plasma pyrolysis are usually comparable with those of lignite and

Table 6
Example data of thermal plasma pyrolysis treatment (wt% on the original material basis; blank entry means data not available)

Feed	Plasma torch	Power (kW)	Feed rate	Particle size	Gas yield (wt%)	Gas product distribution (wt%)							References
						H ₂	CO	CH ₄	C ₂ H ₂	C ₂ H ₄	C ₃ H ₆	CO ₂	
Tire	DC plasma	80	1.5–4 kg/h	500 μm		5–20	4–9	0.6–3	0.5–1			0.5–7	[28]
Tire	DC plasma	60	100 g/min		77	24.1	14.2	1.1	0.4	0.5			[30]
PP	DC plasma	60	100 g/min	60–80 mesh	98	18.3	0.5	2.4	6.3	1.2		0.06	[29]
PP	ICP	10–20	1.5–5 g/min	38 μm	78			2.6		1.7	93.7		[26]
PE	ICP	10–20	1.5–5 g/min	20–90 μm	50			5.6	5.7	22.2	53.4		[27]
Medical waste	DC plasma	50				22.6	26.7	1.5				4.2	[31]
Agricultural residue	DC plasma	40.5	1–4 g/s	20–80 mesh	79	7	53.3	2.7	8.6			3	[32]
Coal	DC plasma	32.5	3.5 kg/h		94	54.9	39.6					4.2	[37]

coke and can be used as a solid fuel directly. Nevertheless, utilization of the char can vary considerably according to their characteristics. For better process economy, other high value applications of solid products are sought.

Usually, waste plastic has a volatile content of more than 90%. By plasma pyrolysis treatment, the conversion efficiency to gas can reach up to 90%, and the amount of solid residue is very small. Guddeti et al. [26] reported that the solid residue contained almost 100% carbon. Several novel carbon structures were observed, indicating the potential of several high value applications of this solid carbon such as production of high surface area catalysts, carbon adsorbent, electronic applications such as super capacitors etc.

In the treatment of waste tires using thermal plasma pyrolysis, one attractive option is to recycle the maximum amount of carbon black filler. Huang et al. [30] investigated extensively the properties of the solid residue from plasma pyrolysis of waste tires and compared them with those of commercial carbon blacks. The results indicated that the sample contains more than 80 wt% of elemental carbon and has a surface area comparable with those of medium grade commercial carbon black. However, the sample contained high ash content, probably from additive constituents, e.g. ZnO, and other inorganic materials added during tire manufacture. In industry, carbon black must be carefully chosen to achieve suitable properties in the compounded rubbers for different applications. Thus, the solid residue mixture from plasma pyrolysis is useful only as a low grade semi-reinforcing filler for non-tire applications and cannot be used directly as a carbon black source for tire manufacture. High grade carbon black may be obtained after further processing of the solid residue mixture by acid and base wash, for instance, and de-ashing [41].

7. Process advantages and application potential

Thermal plasma pyrolysis treatment of organic waste has the following main advantages:

- 1) Efficient delivery of heat energy for simultaneous rapid promotion of both physical and chemical changes in waste material.
- 2) Easy achievement of high and effective processing temperatures in very compact, high throughput and fast response reactors.
- 3) The properties of plasma pyrolysis products are suitable for energy and material recycling.
- 4) Non-polluting and capable of destroying substances harmful to human health, and the products are predictable, harmless and acceptable for public health and environment.

Thermal plasma pyrolysis of organic waste gives only two product streams: a combustible gas and a solid residue; both of which are useful, easy to handle products. In com-

parison, conventional pyrolysis of organic waste usually leads to gas, liquid and solid products. The liquid product is a tarry oil consisting of a variety of heavy hydrocarbon compounds; and separation and collection of the oil from other gas and solid products are difficult.

Thermal plasma reactors need significant amounts of energy input to achieve their high processing temperatures. This makes them costly to operate. However, when the energy content of the pyrolysis products is utilized and recycled, the plasma pyrolysis treatment process is energy self sufficient, so the operating cost is significantly reduced. Thermal plasma technology recently found some applications in places where landfill costs are very high and environmental regulations are strict [33]. Industrial applications of plasma processes are dependent on economic factors. For example, a preliminary analysis indicated that plasma pyrolysis treatment of rubber waste has economic potential, given the following assumptions [30]:

- 1) Capital investment for a plant processing rubber waste 300 kg/h is \$1 500 000.
- 2) Specific energy consumption is 1 kWh/kg rubber feed.
- 3) Electricity price for industrial sector is \$0.05/kWh.
- 4) Carbon black recovery is 23 wt% of rubber feed; market price for semi-reinforcing carbon black is \$500/ton.
- 5) Gate fee for receiving rubber waste is \$30/ton.
- 6) Gas yield is 3 Nm³/kg rubber feed, and with a calorific value of 9 MJ/Nm³; the gas is combusted in a boiler or gas engine for power generation at efficiency of 26%.

8. Concluding remarks

Thermal plasma pyrolysis is in the forefront of modern waste treatment. There is great potential for development of thermal plasma pyrolysis technologies applicable to waste management with energy and material recovery. Although important research progress in this area has been made in recent years, there are still considerable technical challenges to be faced in developing and modifying thermal plasma pyrolysis processes for industrial applications. The rapidly increasing pressure of environmental protection and energy and resources conservation may hasten development and industrial implementation of the technology in the near future.

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