Journal of Scientific & Industrial Research
Vol. 69, March 2010, pp. 177-179

Plasma pyrolysis and gasification of plastics waste – a review

Pragnesh N Dave* and Asim K Joshi

Department of Chemical Engineering, Institute of Technology, Nirma University, Ahmedabad 382 481, India

Received 08 September 2009; revised 29 December 2009; accepted 30 December 2009

Plasma pyrolysis integrates thermo-chemical properties of plasma using pyrolysis process for safe disposal of solid wastes. It is an environment friendly technology to generate valuable byproducts by converting municipal solid waste, biomedical waste and hazardous wastes at 800-1000°C. Plasma Pyrolysis of plastic wastes generates pyrolysis gas, which can be utilized for energy recovery via different applications.

Keywords: Plasma gasification, Plasma pyrolysis of plastics, Plasma technology, Thermal plasma generators

Introduction

Thermal processes (incineration, pyrolysis, melting or vitrification) have been proposed for treating hazardous and municipal solid waste (MSW) prior to disposal. Plasma[1], an ionized gas resulting from an electrical discharge, can be distinguished into high temperature plasma (a thermal equilibrium state) and fusion plasma (quasi-equilibrium plasma and non-equilibrium plasma or cold plasma). Lightning and aurora borealis are most common natural plasma observed on Earth[2]. This review presents current status of plasma technology in treatment of non-biodegradable plastics waste.

Plasma Technology

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. In presence of a sufficiently high gas flow, plasma extends beyond one of the electrodes as a plasma jet[1]. When a sufficiently high voltage difference is applied between two electrodes placed in a gas, latter will break down into positive ions and electrons, giving rise to a gas discharge. Few electrons are emitted from electrodes due to cosmic radiation. Without applying a high voltage difference, electrons emitted from cathode are not able to sustain discharge. Emitted electrons are accelerated by electric field in front of cathode and collide with gas atoms. Most important collisions are inelastic collisions, leading to excitation and ionization. Excitation collisions, followed by de-excitations with emission of radiation, are responsible for glow discharge. Another important process in glow discharge is phenomenon of sputtering, which occurs at sufficiently high voltages.

*Author for correspondence
Tel: +91-0271-241911; Fax: +91-0271-241917
E-mail: pragneshdave@gmail.com

Plasma Pyrolysis

Plasma pyrolysis integrates thermo-chemical properties of plasma with pyrolysis process, which takes place in absence or negligible amount of oxygen. Plasma pyrolysis uses extremely high temperatures (2000-10000 K) of plasma arc to decompose waste material completely into simple molecules. Hot plasmas are particularly appropriate for destruction of toxic molecules. Another advantage of plasma pyrolysis is reduction in volume (> 99%) of organic matter, after releasing ultraviolet radiation. Time for complete waste transformation due to plasma chemistry is 0.01-0.5 s, depending on waste and temperature. Several types of reactions take place in pyrolysis; most common ones being eliminations and rearrangements. Other reactions (oxidation, reduction, substitution, or addition) also are possible. In elimination

Table 1—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%						
						H_2	CO	CH_4	C_2H_2	C_2H_4	C_3H_6	CO_2
Tire	DC plasma	80	1.5-4 kg/h	50 µm								
Tire	DC plasma	60	100 g/min			5-20	4-9	0.6-3	0.5-1			0.5-7
PP	DC plasma	60	100 g/min	60-80 mesh	77	24.1	14.2	1.1	0.4	0.5		
PP	ICP	10-20	1.5-5 g/min	30 µm	98	18.3	0.5	2.4	6.3	1.2		0.06
PE	ICP	10-20	1.5-5 g/min	20-90 µm	78			2.6		1.7	93.7	
Medical waste	DC plasma	50			50	22.6	26.7	1.5				4.2
Agricultural residue	DC plasma	40.5	1-4 g/s	20-80 mesh	79	7	533	2.7	8.6			3
Coal	DC plasma	32.5	3.5 kg/h		94	54.9	39.6					4.2

reaction, fragments of a molecule are removed and form a new molecule. Elimination involves a free radical mechanism. First, an initiation occurs by pyrolytic cleavage, followed by propagation and termination, resulting formation of molecular fragments as[5]

Initiation $$R_2CH\text{-}CH_2X \xrightarrow{\Delta} R_2CH\text{-}CH_2^* + X^*$$

Propagation $$R_2CH\text{-}CH_2X + X^* \xrightarrow{\Delta} R_2C^*\text{-}CH_2X + HX$$

$$R_2C^*\text{-}CH_2X \xrightarrow{\Delta} R_2C{=}CH_2 + X^*$$

Termination $$2R_2C^*\text{-}CH_2X \xrightarrow{\Delta} R_2C{=}CH_2 + R_2CX\,CH_2X$$

$$2X^* \rightarrow X_2$$

where Δ indicates heating. End product yields and properties depend on plastic waste composition.

Plasma pyrolysis of Plastics [Polyethylene (PE), Propylene (PP)]

In pyrolysis, presence of PE increases alkane content, while PS (polystyrene) leads to higher aromatic content in end product. Presence of PP favors alkene formation. Therefore, both PS and PP increase octane number of end product[6]. Thermal degradation of these polymers has been investigated[7] under isothermal conditions using a gradient free reactor with on-line mass spectrometry. Thermal degradation of PE is investigated at 430-480°C at reaction times between 20 min and 6 h. PE decomposes into a large number of paraffinic and olefinic compounds without a residue. A representative mass spectrum obtained in an isothermal run at 480°C shows typical fragmentation pattern of aliphatic compounds. PP also decomposes into a large number of aliphatic compounds without a residue. Representative mass spectrum obtained in an isothermal run at 460°C shows typical fragmentation pattern of aliphatic compounds. Variety of products is more complex than from PE degradation. In first step, saturated compounds were identified[7]. Table 1 presents example data of thermal plasma pyrolysis treatment (wt% on original material basis).

Thermal plasma pyrolysis can also be used as a depolymerization process for monomer recovery from polymer waste when combined with a quench process. Using an induction coupled plasma (ICP) reactor combined with plasma plate power (10-20 kVA) followed by rapid quenching (1000 k/s), waste PP can be depolymerized into propylene. Process is characterized by a high heating rate of feed powder and rapid quenching of product vapor to terminate secondary conversion of product. PP is converted to gas product (78%), mainly propylene[1].

Plasma Gasification

Gasification process, which takes place in substoichiometric quantity of oxygen, converts carbonaceous materials to a combustible or synthetic gas (H_2, CO, CO_2, CH_4). In general, gasification involves reaction of carbon with air, oxygen, steam, carbon dioxide, or a mixture of these gases at 704°C or higher to produce a gaseous product that can be used to provide electric power and heat or as a raw material for synthesis of chemicals, liquid fuels, or other gaseous fuels such as hydrogen[8]. Once a carbonaceous solid or liquid material is converted to a gaseous state, undesirable substances (sulfur compounds and ash) may be removed from gas. In contrast to combustion processes, which work with excess air, gasification process operates at substoichiometric conditions[8]. Combustion that takes place in excess of air (oxygen) gives gases (CO_2, NO_x, SO_x, H_2O), particulate matter etc., pyrolysis results in formation of syngas (H_2 + CO), lighter hydrocarbons and soot particles[1,3,4], whereas gasification results in higher syngas generation and soot particle conversion[9].

Plasma Gasification of Plastics and High Calorific Wastes

Using a steam plasma gasification system, PE is decomposed to give hydrogen (65%) and CO (30%) under steam-PE ratio (1.2) at 1200°C by using a V-type Plasma torch[10]. From experimental results using wood chips and polyolefin sheets as feedstocks, it has been demonstrated that injection of high temperature steam/air mixture into pyrolysis gas can effectively decompose tar components in pyrolysis gas into CO and H_2, resulting in an almost tar-free, clean gas product. Power generation with a dual fueled diesel engine combined with gasification of wastes has been successfully achieved demonstrating as high as 30% engine thermal efficiency[11].

Conclusions

There is great potential for development of thermal plasma pyrolysis and gasification technologies applicable to waste management with recovery of energy and material. Energy and resources conservation may accelerate development of plasma technology in near future.

Acknowledgements

Authors thank Dr S K Nema, Dr S Mukherji and Prof P B Jhala for access to Facilitation Centre for Industrial Plasma Technologies, Gandhinagar and assistance with measurements. AJ thanks National Fusion Programme (NFP) Internship Scheme for granting financial support at Institute for Plasma Research, Gandhingar.

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