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Process Modeling And Simulation In Plasma Technology –An Innovative Approach Towards Sustainable Solution For Solid Waste Treatment

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ABSTRACT: *Recently, thermal plasma process has been proved to be a viable technology for recovering energy and useful products from waste. The purpose of this work is to extend Process modeling to analyze and optimize design of industrial scale thermal plasma reactor for solid waste treatment. Overall technical review of plasma thermal waste treatment technology is provided. Plasma treatment of solid waste involves complex chemical and physical phenomena, such as pyrolysis, char gasification, gas phase reactions, solid-gas multiphase flow, turbulence, radiation heat transfer etc. The comprehensive modeling of these phenomena is an unreachable target. So, key approximations, based on experimental observations, are made in developing Process model. It is demonstrated that Process model can be used for design analysis and optimization of thermal plasma technology for waste treatment. Numerical model is validated against experimental observations and then used in performance evaluation .The model shall be used to predict the amount of syngas produced.*
Keywords - *Plasma, Process modelling, Syngas*

I. INTRODUCTION

Waste management is an important issue in both developed and developing countries nowadays. Today's society uses, and quickly discards, a large volume of an increasingly diverse range of polymeric materials. Organic wastes, such as used rubber and plastic are among the waste materials that represent problematic wastes on one hand and valuable potential as secondary raw materials on the other hand .Most conventional chemical methods cannot deal with Municipal Solid Waste (MSW) due to the diversity of its composition, which range from simple thermoplastics to complex thermosets and composites. Nowadays MSW also contains outdated computer parts and electronic items. Printed Circuit Boards (PCB) are a major part of the waste from electrical and electronic equipment (WEEE); utilization, recycling, and final disposal of these products have become important issues Apart from the municipal solid waste, biomass generated from various agriculture residues (majority coming from rice and wheat straw, corn stalk, cotton stems and bagasse) are wastes, which are used as primary sources of energy for domestic purposes by low-efficiency methods of direct combustion .Biomass is often regarded as a renewable, storable and transportable energy source; it is available in various forms such as wood, agricultural and forest residues, and garbage. Biomass energy is neutral with respect to CO_2 emission, and can significantly alleviate the greenhouse effect caused by fossil fuel consumption. 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 nonconventional sources like MSW and biomass residues. Pyrolysis and gasification are efficient ways for biomass utilization. However, the gas yield from conventional pyrolysis technology is normally below 40 wt% of biomass feed and the accompanying corrosion to the equipments caused by the high content of tar vapor contained in the gas phase is serious. These problems are difficult to overcome due to only limited control of the product composition in pyrolysis and gasification processes. Incineration of organic waste may utilize the energy content of organic waste but is associated with the generation of SO_2, NOx and other hazardous emissions Thermal plasma technology has been under active development for a long time. The technology is now well established in metallurgical processing, materials synthesis etc .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 rather than recycling because of economic issues. Nevertheless, in recent years, the interest in energy and resource recovery from waste has grown significantly. Plasma pyrolysis has a number of unique advantages over conventional pyrolysis. It provides high temperature and high energy for reaction. The reaction sample is heated up to a high temperature rapidly, and some reactions occur that do not appear in conventional pyrolysis. It is an appropriate method for polymer pyrolysis. It also produces a gas with low tar content and high heating value, which can be applied well to gas turbines for power generation or used as a synthesis gas for hydrogen production and can also be used to produce Ethanol from Synthesis gas There is a tremendous scope for applying plasma assisted pyrolysis of assorted non-nuclear waste such as biomass, printed circuit boards, organic waste, medical waste etc, for obtaining useful energy. The objectives of the study were to Study the overall Process of Plasma Technology, Designing a Computational Process Model and its validation with actual data.

II. PLASMA REACTOR

Waste from the waste feed system enters into the plasma reactor where the high temperatures created by the plasma torches dissociates the molecules that make-up the waste components into their elemental constituents. Before waste is charged into the plasma reactor, it is ensured that the bulk temperature of the reactor is a minimum 800°C. The bulk temperature of the plasma reactor is maintained at 1,000°C to 1200°C during normal conditions. This also ensures the bulk temperature of the plasma reactor bottom is in the range of 1400-1500°C at a steady state condition. The plasma reactor provides 2.0 seconds of residence time for the synthesis gas to ensure complete destruction of waste. Additional polishing chamber is provided in plasma reactor for where steam is injected as oxidant to ensure complete reaction of C to form CO and hydrogen. Reaction zone and polishing zone in the reactor is separated by baffle wall.

Waste destruction in the plasma reactor can be described by following chemical reactions

C	+	H_2O	=	CO	+	H_2	(Endothermic Reaction)
C	+	$2H_2O$	=	CO_2	+	$2H_2$	(Endothermic Reaction)
C	+	O2	=	CO2			(Exothermic Reaction)
C	+	CO_2	=	2CO			(Exothermic Reaction)
H_2	+	2Cl	=	2HCl			(Exothermic Reaction)
H_2	+	S	=	H_2S			(Exothermic Reaction)

In the plasma reactor waste will first dissociate into the elemental form and then reacts with steam (H_2O). Thus, as shown in the above reactions Carbon (C) will be converted to Carbon Monoxide (CO) and Carbon Dioxide (CO_2), Water will be dissociated into Hydrogen (H_2) and Oxygen (O_2). Chlorine (Cl) and Sulfur (S) will combine with Hydrogen to form Hydrogen Chloride (HCl) and Hydrogen Sulfide (H_2S), respectively. Oxygen required for the formation of CO and CO_2 is supplied by the O2 liberated by dissociation of H2O, Oxygen present in waste and Air leakage into system. The balance of Oxygen required is supplied by an Oxygen cylinder through the Oxygen lance system. The product gas from the plasma reactor will consist of CO, CO_2, H_2, HCl, H_2S, N_2 and unreacted carbon particles. This is called synthesis gas ("syngas"). The heat value of Syn Gas is contributed by the CO and H_2. The synthesis gas from the plasma reactor is piped to the Venturi Scrubber for Conditioning and Cleaning. The inorganic part of the waste will remain at the bottom of the reactor and will form a vitrified matrix at a temperature of 1400-1500°C. In order to reduce the melting point and viscosity of the matrix, flux can be added to the reactor along with waste. The quantity of the flux can be in range of 2-4% of the waste quantity. Sodium carbonate or calcium carbonate can be used as flux material. For the Plasma Reactor, sodium carbonate should be used as the flux material. Removing the matrix from the reactor bottom is called slag-matrix tapping process.

III. PROCESS MODELLING AND SIMULATION

Microsoft Excel is used to prepare Mass Balances and Process Flow sheet and to design a complete model to predict the composition of Syngas. The model is used to describe the theoretical concepts and computational methods that represent and simulate the functioning of real-world processes. Models are simplified abstractions of reality representing or describing its most important/driving elements and their interactions. Simulations can be regarded as model runs for certain initial conditions (real or designed)

A Basis for Design

The plasma reactor is designed based in syngas mode. Waste is fed on continuous basis through shredder and screw feed system in to the plasma reactor. Waste is gasified in plasma reactor with help of bottom mounted transferred arc torches of 100 KW capacity. IGBT based DC power supply system is provided for energizing plasma torches. Syngas generated in plasma reactor is quenched and cleaned in wet scrubbing system for removal of particulate matter and gaseous pollutants generated. Syngas such produced will be then available for use in downstream syngas utilization system for energy or power generation. Final flue gas from the syn gas utilization system meets the desired emission norms. PTDR-system is provided with PLC based SCADA system and computer terminal as operating console for the single point operation and monitoring of the plant. Plant can be operated on continuous basis up to 16-18 hours. Separate time is required for slag making and slag tapping accumulated at the bottom of the reactor.

Basis/Input includes:

- Waste input/feed rate (Kg/Hr)
- Waste ultimate characteristics (i.e. Carbon, hydrogen, oxygen, nitrogen, chlorine, sulphur, metal, water etc.) (% by weight)
- Air leakage assumption (Kg/hr)

Outcome of the model includes:

- Gaseous constituents concentration upstream of Air Pollution Control Devices (APCD) (i.e. CO, H_2, CO_2, N_2, H_2S, HCl/acidic gases, PM, H_2O) (% by Vol., Kg/hr, kmoles/hr)
- Gaseous constituents concentration downstream of Air Pollution Control Devices (APCD) (i.e. CO, H_2, CO_2, N_2, H_2S, HCl/acidic gases, H_2O) (% by Vol., Kg/hr, kmoles/hr)
- Total Energy required by PLASMA electrodes/for arcing inside reactor to maintain minimum 1200-1300 Deg C.
- NaOH required to neutralize acidic gases in cleaning system
- Heat value of Syngas (Kcal/m^3)
- Synthesis gas produced in the process Total energy/electricity production by syngas produced by means of gas engine or gas turbine.

B Waste Source

The waste source was Bio Medical Waste.

C Physical Form of Waste:

The Waste was in the form of loose solid waste, semi solid waste or small liquid containers. Solid and semi-solid types of waste are required to be packed into suitable size of High-density polyethylene packing and/or carton packing or liquid carboy (up to limited capacity) in order to avoid spillage during transferring waste from ground level to inlet of feed hopper. The maximum size of the packing was 300 mm x 300 mm x 300 mm. Waste feed system consist of shredder with screw feeding system.

D Waste Characteristics

The plasma reactor is designed based on ultimate analysis of waste as provided in Table 1

Table 1: Waste Ultimate Analysis

UTLIMATE CHARACTERISTICS OF WASTE MIXTURE (% by Weight)	
Component	**% By weight**
Carbon as C	36.78
Hydrogen as H	7.3
Chlorine as Cl	1.6
Oxygen as O	25.88
Nitrogen as N	0.57
Sulfur as S	0.19
Water as H_2O	18.0
Inorganic	9.68
Total	**100**

III RESULTS

The Waste Feed Rate assumed for simulation was 60 kg/hr. As per the weight Composition of waste Feed Rate in the reactor the kmoles/hr of waste in the feed is calculated, as given in the table 2

Table 2: Ultimate Characteristics of Waste Mixture (kmoles/Hr)

UTLIMATE CHARACTERISTICS OF WASTE MIXTURE	% by wt	Molecular Weight	Kg/Hr	kmoles/Hr
CARBON	36.78000%	12	22.068	1.839
HYDROGEN (H_2)	7.30000%	2.016	4.38	2.172619048
CHLORINE (Cl_2)	1.60000%	70.9	0.96	0.013540197
OXYGEN (O_2)	25.88000%	32	15.528	0.48525
NITROGEN (N_2)	0.57000%	28	0.342	0.012214286
SULFUR (S)	0.19000%	32.06	0.114	0.003555833
WATER (H_2O)	18.00000%	18.02	10.8	0.599334073
METALS	0.00000%	NA	0	
INORGANICS	9.68000%	NA	5.808	
TOTAL	100%			

Air Leakage is assumed to be 25 m^3/Hr. With respect to the total leakage of Air the amount of oxygen and Nitrogen from Air leakage is calculated in kmoles/hr and m^3/hr as given in the table 3 which will contribute in the reactions.

Table 3: Air Leakage Assumption in the rector

	M.W	Kg/hr	kmoles/hr	m^3/hr	Density (Kg/m^3)
Air Leakages (Assumed) (m^3/hr)	28	32	1.1428571	25	1.28
Oxygen Available from Air Leakages	32	7.145	0.2232812	5	1.429
Nitrogen Available from Air Leakages	28	24.68	0.8816964	19.75	1.25

Table 4: Gas composition upstream of APCD (Air Pollution Control Devices)

GAS Composition upstream of APCD							
Component	**kmoles/Hr**	**M.W.**	**Kg/Hr**	**Density**	**m^3/Hr**	**Volume%**	**Weight%**
CO	1.467043539	28	41.07721911	0.231599	177.3634	26.58456	46.07699673
CO_2	0.371956461	44	16.36608426	0.363942	44.96898	6.74029	18.35810767
H_2	2.754857091	2.02	5.564811323	0.016708	333.0581	49.92126	6.242140991
N_2	0.893910714	28	25.0295	0.231599	108.0725	16.19872	28.07600453
HCl	0.027080395	36.5	0.988434415	0.301906	3.27398	0.490729	1.108743247
H2S	0.003555833	34.6	0.123031815	0.28619	0.429895	0.064436	0.138006824
Total			89.14908092		667.1669	100	100

Neutralization in Air Pollution Control Devices

The gas conditioning and cleaning system is provided to cool down the syngas to a saturation temperature, to remove particulate matter, to remove gaseous pollutants generated from pyrolysis such as H_2S and HCl. The gas conditioning and cleaning system is provided with a venturi scrubber, a packed bed scrubber, a common scrubber circulation tank and pump, a heat exchanger, a bleed liquid filtration system and a caustic dosing system. Downstream of the venturi scrubber is a counter-current flow packed bed scrubber, used for further removal of any entrained particulate matter and to carry out the chemical absorption of acid gases such as H_2S and HCl. In order to ensure an efficient absorption of these acidic gases, the scrubber circulation liquid is maintained at 9-10 pH. This is maintained by the continuous dosing of a caustic solution through the caustic solution dosing pump from the caustic solution dosing tank.

The Neutralization Reaction is as follows:

$HCl + NaOH = NaCl + H_2O$

$H_2S + 2NaOH = Na_2S + 2H_2O$

Table 5: Final Gas composition Downstream of APCD (Air pollution Control Devices)

SYNGAS Composition Downstream of APCD (Air Pollution Control Devices)						
	kmoles/hr	**Molecular Weight**	**Kg/hr**	**Density(kg/ m^3)**	**m^3/hr**	**Volume %**
CO	1.467043539	28	41.07721911	1.145	35.8753	25.0746
CO_2	0.371956461	44	16.36608426	1.98	8.265699	5.777208
H_2	2.754857091	2.02	5.564811323	0.0898	61.96895	43.31243
N_2	0.893910714	28	25.0295	1.25	20.0236	13.99525
HCl	2.70804E-05	36.5	0.000988434	1.528	0.000647	0.000452
H_2S	3.55583E-06	34.6	0.000123032	1.39	8.85E-05	6.19E-05
PM	0	18	0	0.804	0	0
Water	0.7	12.1	8.47	0.5	16.94	11.84
Total			**96.50872616**		**143.0743**	**100**

IV. CONCLUSION

The predictive capabilities of numerical model are demonstrated by composition of Syngas. The reliability of numerical simulations is verified by comparing experimental data with actual data. The results obtained were validated with the actual results. The Deviation from the actual value was also calculated which are tabulated below-

Table 6: Validation of Results

SynGas Composition	Predicted (Volume %)	Measured (Volume %)	Deviation (Percentage)
CO	25.0746	23.37	6.79%
CO_2	5.777208	6.01	4.03%
H_2	43.31243	47.01	7.87%
N_2	13.99525	13.22	5.50%
H_2O	11.88	10.38	12.62%

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