A comparative analysis of pyrolysis and gasification of tyre waste by thermal plasma technology for environmentally sound waste disposal

Gloria James [a,*], S.K Nema [b], Anantha Singh T. S. [a], P. Vadivel Murugan [b]
[a] Pandit Deendayal Petroleum University, Gujarat, India
[b] Institute of Plasma Research, Gujarat, India

Abstract

The usage of tyre has increased enormously in day to day life. The used tyre and rubber products pose major threat to the environment. Conventional thermal techniques such as incineration produce high molecular organic compounds (condensed and collected as aromatic oil) and carbon soot particles. Plasma based pyrolysis and gasification technique can dispose tyre waste and generate combustible gases which can be used as a fuel and avoid the formation of higher molecular aromatic compounds. In this work plasma gasification and plasma pyrolysis of waste tyres have been conducted in a batch reactor having graphite electrodes and direct current (DC) arc plasma system. The process temperature was maintained at 700°C- 800°C and the material was fed at a constant rate of 1 kg/6 min. The two processes are compared based on the gas composition, syngas yield, char yield and efficiency of the process. Results indicate 4% increase in syngas yield in plasma gasification than in plasma pyrolysis. The syngas analysis shows that higher amount of CO and H_2 are obtained and 8.18% rise in cold gas efficiency (CGE) in plasma gasification compared to plasma pyrolysis. The results suggest plasma gasification as a better alternative than plasma pyrolysis.

Keywords: Gasification, Plasma, Pyrolysis, Syngas, Tyre waste

1. Introduction

Tire production is rising due to increasing demand of vehicles. It is estimated that more than 5×10^6 tons of tires are produced worldwide annually [1, 2]. Due to the increased production of tires the waste tire generation is also increasing. Disposal of waste tire is an environmental challenge as tires are made of complex substances like natural rubber, butadiene, styrene butadiene which are difficult to degrade [3]. A major part of tyres are land-filled, while the remaining are recycled and reused for various purposes such as recycling by production of ground rubber, reclaiming of rubber products from scrap rubber or tires [4,5]. But all these are cost and energy intensive methods. Another alternative for this is thermal treatment which includes gasification and pyrolysis.

Pyrolysis is a method of thermal decomposition at elevated temperatures in absence of oxygen. Unlike incineration which generates lot of toxic gases like SO_x, NO_x, pyrolysis is an environment friendly method. The gases generated by tyre pyrolysis are carbon monoxide (CO), carbon dioxide(CO_2), hydrogen sulphide (H_2S), methane (CH_4), ethane (C_2H_4), ethene (C_2H_4), propane

*Corresponding author Tel: +91 9586265817
Email : gloriajames17@gmail.com

(C_3H_8), propene (C_3H_6), butane (C_4H_{10}), butene (C_4H_8) and butadiene (C_4H_6) [6-8]. These gases generated can be used as a fuel internally to provide process heat [9-13]. Pyrolysis generates solid char (30-40 wt %), liquid residue (40-60 wt %) and gases (5-20 wt %). The solid char after processing can be utilized as an activated carbon in wastewater treatment.

Tyre waste can also be decomposed in the presence of oxygen. This process is called gasification. Gasification is the process of partial combustion of the substance as oxygen is fed at sub-stoichiometric ratio. It increases the gas yields and produces fuel having higher calorific value which can be used internally in gasification cycle or as a replacement for ignition oils in coal fired power plants [14, 15].The gasification and pyrolysis process can be further enhanced by using plasma as a power source. Plasma being fourth state of matter consists of electrons, ions, atoms and radicals because of which it is able to produce very high concentrations of chemically active species [16].This produces high energy density and high temperatures.

Most part of the literature data on plasma gasification is based on hazardous waste, plastic waste, biomedical waste, while data concerning with plasma gasification of tyre waste is hardly found. Hence this work aims to study the plasma gasification and plasma pyrolysis of tyre waste with the goal being to compare both of these on the basis of gas compositions, char yield and efficiency of the process.

2. Experimental

2.1 Tyre samples

The shredded tyre waste used in this experimental work was procured from a tyre recycling plant in Ahmedabad. The average size of the shredded tyres was 20 mm. 1 kg of tyre waste was fed in every 6 minutes cycle. The calorific value of the tyre was determined by bomb calorimeter. The proximate analysis was done to find out ash, volatile and moisture content. The fixed carbon was determined by the difference [17].The ultimate analysis of the sample was analyzed by Perkin and Elmer CHNS Elemental analyzer. The HHV (High heating value) of tyre waste was determined by bomb calorimeter. The tyre waste analysis is summarized in Table 1.

Table 1

Proximate and ultimate analysis of tyre waste

Proximate analysis (wt %)		Ultimate analysis (wt %)	
Fixed carbon[a]	21.33	Carbon	81.93
Volatile matter	65.19	Hydrogen	6.27
Ash	12.57	Nitrogen	-
Moisture	0.91	Sulphur	3.21
HHV	33.4MJ/Kg	Oxygen[a]	8.59

[a] (by difference)

2.2. Pyrolysis and gasifier unit

The schematic diagram of the process is shown in Fig.1. The main sub units of the plasma gasification reactor is process chamber, feeder assembly, combustion chamber, scrubber unit, ID fan and plasma torch.

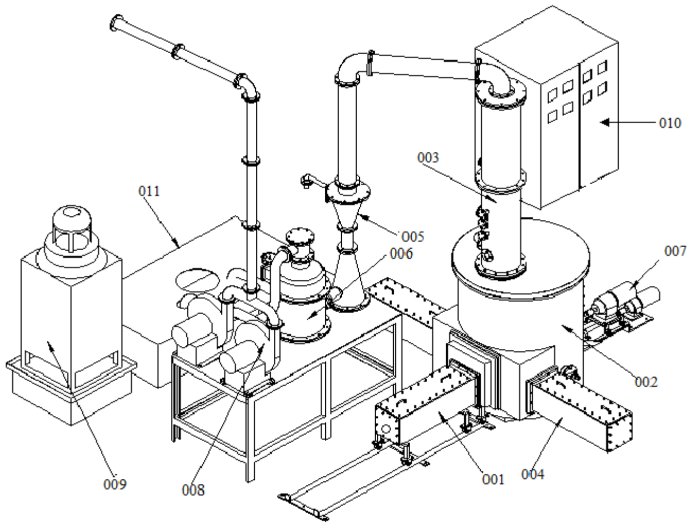

Fig.1. Schematic diagram of the plasma waste processing plant

Process chamber consists of a mild steel tubular reactor (700 mm i.d. and 1200 mm in length). Insulation lining is provided inside to prevent heat loss. The feeder system consists of an opening of 400 mm x 400mm connected to the process chamber. The waste fed from the opening, falls into the process chamber. After the waste tyre is fed, it is combusted in the process chamber, the gases produced passes through a secondary combustion chamber where any toxic gases formed like furans and dioxins are combusted to form CO_2. Gases after passing through the combustion chamber goes through the cleaning system which consists of venturi scrubber and packed bed scrubber which brings down the gas temperature to 70°C. The scrubber unit is connected to the water jet which quenches the flue gas and removes the soot particles. ID fan is connected to the system which maintains a negative pressure in the system. The temperature of the inner wall of the reactor is measured by four thermocouples located at different positions. The heat source of the system consists of a non transferred type DC plasma torch consisting of two graphite electrodes anode and cathode.

2.3 Experimental methodology

Plasma Pyrolysis

The waste tyre is fed into the reactor through carton boxes. The waste tyres are fed after the reactor has been preheated and the desired temperature is reached. The operating temperature of the process is from 500 – 700°C. Nitrogen is used as a carrier gas to extend the arc produced between the electrodes. The flow rate of nitrogen is maintained at 25- 30 lpm.

Plasma Gasification

In the gasification process oxygen is used as a gasifying agent that is fed into the reactor through a shower made of mild steel having diameter 700 mm with 20 holes of 2 mm diameter each. Oxygen is fed after feeding the waste tyres. When sufficient number of tyres has been fed and the system stabilizes to produce flame in the secondary chamber, the gas sample is collected in sampling cylinders through pump. This gas is then analyzed in gas chromatograph for analysis of different components in the gas i.e. CO, CO_2, H_2, and CH_4. The char remaining after the gasification process is collected and weighed for char yield. The operational and process parameters for the plasma pyrolysis (T1) and plasma gasification (T2) process are shown in Table 2.

Table 2
Operational and process parameters

Test	Pressure(bar)	Power(KW)	Temperature (°C)	N_2 flow rate(lpm)	O_2 flow rate(lpm)	Material feed rate (kg/hr)
T1	1	40-50	700-800	25-30	0	10
T2	1	40-50	700-800	25-30	20	10

3. Results and discussion

3.1 Gas characterization

The two processes are compared based on the syngas composition, HHV (Higher heating value), char and syngas yield. Gas composition of the syngas was done by gas chromatography (CIC Dhruva model). The instrument was equipped with porapak Q column. The system had thermal conductivity detector (TCD) and flame ionization detector (FID). Nitrogen was used as a carrier gas in both the cases. The principal gas components analyzed are CO, CO_2, H_2 and CH_4. This is depicted in the graph shown in Fig. 2. As depicted in the graph, the gaseous components has higher amount of H2 and CO in plasma gasification than plasma pyrolysis process. H2 and CO increased from 24.7 and 50.9 to 29.6 and 53.3 respectively.CO_2 content also increased by 4.4% in plasma gasification. This is due to the fact that as the oxygen content increases, it oxidizes the substance into CO, CO_2 and H_2 and hence enhances the formation of syngas. The CH4 content decreased to 6.3% from 8.6%. This shows that fewer amounts of hydrocarbons were produced because of oxidation. Similar results have been shown in other published papers [18].

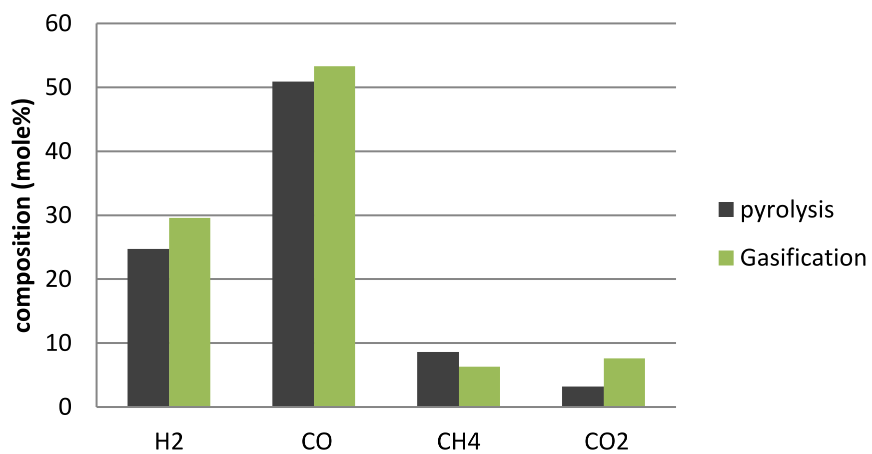

Fig.2. Gas composition of plasma pyrolysis and plasma gasification

3.2 Energy content of the gas and efficiency of the process

The HHV (Higher heating value) is calculated with respect to the components of the gases. The HHV of the syngas increased from 47.45 in plasma pyrolysis to 56.11 in plasma gasification process. This confirms that plasma gasification produces fuel having higher calorific value than the plasma pyrolysis. However in both the processes the syngas produced can be used as a fuel internally in the process.
The CGE (cold gas efficiency) of the process was calculated based on the equation 1 [18-20], where m_{syngas} and m_{feed} are the mass flow rate of syngas and feed respectively, while LHV_{syngas} and LHV_{feed} are the lower heating value of syngas and feed respectively. W_{torch} is the overall power requirement by the plasma torch. The CGE value increased by 8.18% since plasma gasification produced syngas having higher calorific value. This shows that plasma gasification has a higher efficiency than plasma pyrolysis.

$$\text{CGE} = \frac{m_{syngas} \cdot LHV_{syngas}}{m_{feed} \cdot LHV_{feed} + W_{torch}} * 100 \qquad (1)$$

Table 3
HHV and CGE of the process

	Plasma Pyrolysis	**Plasma Gasification**
HHV(MJ/Kg)	47.45	54.50
CGE (%)	56.19	64.37

3.3 char and gas yield

The char yield was determined by weighing the amount of char left. As shown in Fig. 3 the char yield decreased by 4% as the oxygen flow rate increased. The syngas production increased in case of gasification, as increase in oxygen flow rate oxidizes the substance and enhances the formation of CO and CO_2. Similar results were obtained by other researchers [21 22].
However it is seen that there is very little influence of oxygen flow rate on char yield. Various other factors also influence in the yield of chars and syngas such as the size of the reactor, gas residence time, reactor temperature and pressure [23, 5].

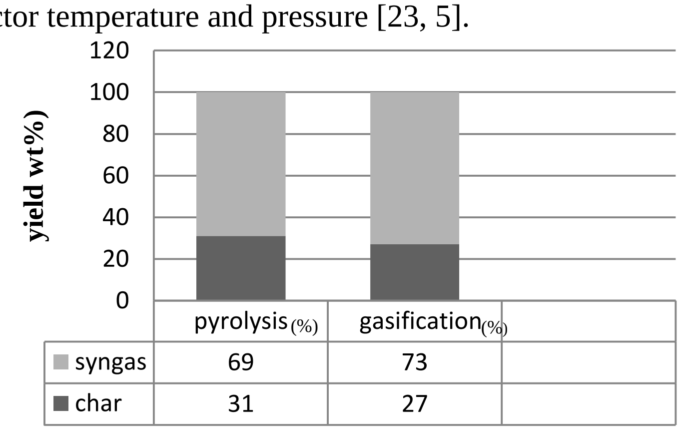

Fig.3. Char and syngas yield

3.4 Elemental analysis

Elemental analysis of the char was determined by EDX. The carbon content in the char decreased in gasification than pyrolysis. As the oxygen flow rate increases, more carbons are oxidized to form CO, CO2 and other hydrocarbons. Hence more carbon is in the gaseous state than in the solid form (char).

Table 4
Elemental composition of char

Element	Pyrolysis (wt %)	Gasification (wt %)
C	64.51	54.28
O	7.12	27.51
Na	2.29	0.83
Mg	0.65	0.16
Al	0.15	2.41
Si	0.81	2.17
S	3.10	2.9
K	0.02	0.05
Ca	0.06	5.63
Fe	0.91	0.80
Zn	20.38	2.31
Zr	-	0.97

4. Conclusion

Based on the experimental work done the following conclusions can be drawn on plasma pyrolysis and plasma gasification of waste tyres:

The char yield and syngas yield for plasma gasification were 27% and 73% respectively. While for plasma pyrolysis process the char and syngas yield was 31% and 69% respectively. Plasma gasification process enhances the formation of syngas thereby increasing its yield while reducing the char yield compared to plasma pyrolysis process.

The syngas produced by plasma gasification process has higher calorific value than plasma pyrolysis. But both the processes have the potential to produce syngas that can be utilized as a fuel. Also plasma gasification has 8.18% higher CGE than plasma pyrolysis.

Acknowledgement

The authors acknowledge the support received by Institute of Plasma Research for carrying out the experiments and conducting the research work. Also the authors would like to thank Gujarat Energy Research and Management Institute (GERMI) for helping in the analysis.

References

[1] Galvagno, S., Casu, S., Casabianca, T., Calabrese, A. and Cornacchia, G., 2002. Pyrolysis process for the treatment of scrap tyres: preliminary experimental results. *Waste management*, 22(8), pp.917-923.

[2] Snyder, R.H., 1998. Scrap tires-disposal and Reuse.

[3] Miguel, G.S., Fowler, G.D. and Sollars, C.J., 1998. Pyrolysis of tire rubber: porosity and adsorption characteristics of the pyrolytic chars. *Industrial & engineering chemistry research*, *37*(6), pp.2430-2435.

[4] Rani, S., Agnihotri, R., 2014. Recycling of Scrap Tyres. *International Journal of Materials Science and Application*, 3(5), pp. 164-167.

[5] Juma, M., Koreňová, Z., Markoš, J., Annus, J. and Jelemenský, Ľ., 2006. Pyrolysis and combustion of scrap tire. *Petroleum & Coal*, *48*(1), pp.15-26.

[6] Laresgoiti, M.F., de Marco, I., Torres, A., Caballero, B., Cabrero, M.A. and Chomón, M.J., 2000. Chromatographic analysis of the gases obtained in tyre pyrolysis. *Journal of Analytical and Applied Pyrolysis*, *55*(1), pp.43-54.

[7] Williams, P.T., Besler, S. and Taylor, D.T., 1990. The pyrolysis of scrap automotive tyres: The influence of temperature and heating rate on product composition. *Fuel*, *69*(12), pp.1474-1482.

[8] Roy, C., Labrecque, B. and de Caumia, B., 1990. Recycling of scrap tires to oil and carbon black by vacuum pyrolysis. *Resources, Conservation and Recycling*, *4*(3), pp.203-213.

[9] Miguel, G.S., Fowler, G.D. and Sollars, C.J., 1998. Pyrolysis of tire rubber: porosity and adsorption characteristics of the pyrolytic chars. *Industrial & engineering chemistry research*, *37*(6), pp.2430-2435.

[10] Barbooti, M.M., Mohamed, T.J., Hussain, A.A. and Abas, F.O., 2004. Optimization of pyrolysis conditions of scrap tires under inert gas atmosphere. *Journal of Analytical and Applied Pyrolysis*, *72*(1), pp.165-170.

[11] Roy, C., Chaala, A. and Darmstadt, H., 1999. The vacuum pyrolysis of used tires: End-uses for oil and carbon black products. *Journal of analytical and applied pyrolysis*, *51*(1-2), pp.201-221.

[12] Bouvier, J.M. and Gelus, M., 1986. Pyrolysis of rubber wastes in heavy oils and use of the products. *Resources and Conservation*, *12*(2), pp.77-93.

[13] Bridgwater, A.V., Toft, A.J. and Brammer, J.G., 2002. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. *Renewable and Sustainable Energy Reviews*, *6*(3), pp.181-246.

[14] Chang, J.S., Gu, B.W., Looy, P.C., Chu, F.Y. and Simpson, C.J., 1996. Thermal plasma pyrolysis of used old tires for production of syngas. *Journal of Environmental Science & Health Part A*, *31*(7), pp.1781-1799.

[15] Gu, B.W., Chang, J.S., Chu, F.Y., Simpson, C.J., 1993. An investigation of syngas production from used automobile tires by thermal pyrolysis. *Proceedings of the 11th Int. Symp. Plasma Chemistry*, pp. 692-697.

[16] Fridman, A., 2008. *Plasma chemistry*. Cambridge university press.

[17] Rasheed, M.A., Rao, P.S., Boruah, A., Hasan, S.Z., Patel, A., Velani, V. and Patel, K., 2015. Geochemical characterization of coals using proximate and ultimate analysis of Tadkeshwar Coals, Gujarat. *Geosciences*, *5*(4), pp.113-119.

[18] Mazzoni, L., Almazrouei, M., Ghenai, C. and Janajreh, I., 2017. A comparison of energy recovery from MSW through plasma gasification and entrained flow gasification. *Energy Procedia*, *142*, pp.3480-3485.

[19] Agon, N., Hrabovský, M., Chumak, O., Hlína, M., Kopecký, V., Masláni, A., Bosmans, A., Helsen, L., Skoblja, S., Van Oost, G. and Vierendeels, J., 2016. Plasma gasification of refuse derived fuel in a single-stage system using different gasifying agents. *Waste management*, *47*, pp.246-255.

[20]Mazzoni, L. and Janajreh, I., 2017. Plasma gasification of municipal solid waste with variable content of plastic solid waste for enhanced energy recovery. *International Journal of Hydrogen Energy*, *42*(30), pp.19446-19457.

[21] Leung, D.Y.C. and Wang, C.L., 2003. Fluidized-bed gasification of waste tire powders. *Fuel Processing Technology*, *84*(1-3), pp.175-196

[22] Lee, J.M., Lee, J.S., Kim, J.R. and Kim, S.D., 1995. Pyrolysis of waste tires with partial oxidation in a fluidized-bed reactor. *Energy*, *20*(10), pp.969-976.

[23] Cunliffe, A.M. and Williams, P.T., 1998. Composition of oils derived from the batch pyrolysis of tyres. *Journal of Analytical and applied Pyrolysis*, *44*(2), pp.131-152.