Plasma for environment

G Van Oost\textsuperscript{1,2}
\textsuperscript{1}Department of Applied Physics, Ghent University, Belgium
\textsuperscript{2}National Research Nuclear University MEPhI, Moscow, Russia

E-mail: guido.vanoost@ugent.be

Abstract. Human activity is associated with the permanent emergence of a very wide range of waste streams. The most widely used treatment of waste is thermal processing such as incineration. An alternative environmentally friendly process is based on thermal plasma technology which is a very flexible tool because it allows to operate in a wide temperature range with almost any chemical composition of waste and chemicals needed for processing this waste, and to convert organic waste into energy or chemical substances as well as to destroy toxic organic compounds, and to vitrify radioactive waste in a scenario that for each specific type of waste can be considered optimal, both in terms of energy efficiency and environmental safety.

1. Introduction

The increasingly stringent legislation on treatment of waste streams and the limitations of conventional technologies such as thermal incineration, catalytic oxidation and adsorption render plasma technologies more and more attractive in comparison with incineration and landfill. The driving force is to give priority to environmental quality at affordable cost, and to contribute to sustainable development.

The present paper deals with the use of thermal plasmas for the treatment of waste \cite{1}. The use of electric-arc plasma (plasma torches or plasmatrons) with mean temperatures of order 5000 K allows the efficient destruction of organic compounds with very high speed and a high degree of conversion. Since the environmental legislation becomes more and more stringent, for the overall evaluation of the technical and economic feasibility of thermal plasma technology, its substantial environmental advantages have to be taken into account in the comparison with non-plasma methods. Three examples of thermal plasma treatment of waste are given from the author’s personal experience.

2. Gasification and vitrification by thermal plasma

Since the 1980s applications of thermal plasmas experienced an important increase. In the 1990s fundamental research led to great progress in the understanding of the basic phenomena involved, and to a renewed interest in applying thermal plasmas to material processing and waste treatment. The application of plasma torches for environmental purposes is a relatively new process. Generators of thermal plasma (plasma torches) operate simultaneously as a plasma-chemical and a thermal apparatus. Plasma is the state of matter with the highest energy content per particle. Therefore, thermal plasma offers the unique capability of carrying an extremely high energy by a small amount of plasma and ensures high heat transfer to the material to be treated. All materials can be decomposed if they are brought in contact with thermal plasma. The electrical energy of the torch goes into the plasma which transfers its energy to the substances to be treated, thereby triggering a dual simultaneous reaction process in the plasma-chemical reactor: the organic compounds are thermally decomposed into their constituent elements (principally a mixture of carbon monoxide and hydrogen, called syngas with more complete conversion of C into gas than in incinerators), and the inorganic materials are melted and converted into a dense, inert, non-leachable vitrified slag that does not require controlled disposal. Therefore, it can be viewed as a totally closed treatment system. The main goal of plasma treatment of organic waste is to produce syngas, while
the main goal of incineration is material decomposition. The use of thermal plasmas has the following advantages:

- Far higher temperatures than can be reached by conventional heat generators
- Highly reactive and reducing environment
- High energy density and heat transfer efficiency, allowing shorter residence times and large throughputs
- Low thermal inertia and easy feedback control
- Lower plasma gas input per unit heating power than the gas flow of a classical burner and thus lower energy loss corresponding to the energy necessary for heating of gas to reaction temperature; also lower amount of off-gases to be treated
- Absence of combustion gases generated by conventional incinerators
- Smaller plants than for incinerators due to high energy densities, lower gas flows, and volume reduction
- Heat source is electricity rather than energy liberated from combustion and thus independent of the treated substances, providing flexibility, fast process control, and more options in process chemistry, including the possibility of generating valuable co-products
- Optimal control of the composition of the reaction gases
- As sufficiently high temperatures and homogeneous temperature distribution can be easily maintained in the whole reactor volume, the production of higher hydrocarbons, tars and other molecules is substantially reduced in comparison with incineration.

3. Gasification of biomass

Conventional biomass gasification technologies are based on the reaction between a solid or liquid carbonaceous material (containing mostly chemically bound carbon, hydrogen and oxygen) and limited amounts of air or oxygen. The exothermic reactions provide sufficient energy to produce a primary gaseous product containing mostly CO, H2, CO2 and H2O (g) and a small amount of higher hydrocarbons. Usually some heat is supplied into the reactor from external sources to control the process, but most of the heat comes from the calorific value of the biomass. The main problem of common biomass gasification is the production of tar. Thermal plasma offers the possibility of decomposition of biomass by gasification or by pure pyrolysis in the absence of oxygen. The main advantage is a better control of the composition of the produced gas, higher heat capacity of the gas and reduction of unwanted contaminants like tar, CO2 and higher hydrocarbons. Most of the experiments with plasma gasification/pyrolysis have been performed with electric-arc plasma torches with relatively high flow rates of plasma gas. The high flow rate of plasma ensures good mixing of plasma with the treated material and a uniform temperature in the reactor. However, the produced syngas contains plasma gas components, usually nitrogen and oxygen. The usage of mixtures of inert gas with hydrogen eliminates this disadvantage but it increases the costs. Therefore, steam is being used as plasma gas.

The present section presents experimental results obtained in the medium scale thermal plasma gasification reactor equipped with a hybrid (gas-water) plasma torch with arc power up to 160 kW at the Czech Academy of Sciences (IPP-CAS) in Prague. The DC plasma torch with gas/water stabilized arc, developed and patented by IPP-CAS and usually applied for plasma spraying, is used [2]. The plasma jet contains a mixture of steam with a small amount of argon. The hybrid torch is composed of two stabilizing chambers. Plasma produced in the cathode arc chamber with gas stabilization enters the second chamber with water stabilization. The gas flow in the cathode part of the torch protects the cathode tip and hence the consumable carbon cathode used in water torches can be replaced by a fixed tungsten cathode. Arc characteristics are dominated by processes in the water-stabilized part of the arc column which is much longer than the cathode section. Due to the principle of arc stabilization by a water vortex the flow rate of plasma gas (typically 0.3g/s H2O plus 0.2g/s Ar) is very low, the plasma enthalpy is higher than 200 MJ/kg, and the mean plasma temperature is higher than 15000 K. By changing the argon flow rate the hybrid torch provides the possibility of controlling the parameters of the plasma jet and the plasma composition (O-H-Ar) in a wide range from high enthalpy, low density plasmas typical for water stabilized torches to lower enthalpy, higher density plasmas generated in gas stabilized torches. An important characteristic feature of this hybrid torch is the very low mass flow rate of plasma. As a low amount of plasma carries high energy, the power needed for heating of plasma to reaction temperature is very low, and the efficiency of utilizing plasma power for waste destruction is extremely high. The clean synthesis gas consists mainly of hydrogen and CO (together minimum 90%).

The experimental plasma-chemical reactor (Fig.1) with water-cooling system has been designed to operate at a wall temperature up to 1700°C [3-4]. The inner volume of the reactor is 0.22 m³. The inner lining of the reactor is made from special refractory ceramics. The insulating 400 mm thick ceramic liner reduces power losses to the walls. All parts of the reactor chamber are water cooled and calorimetric measurements on cooling circuits are
made. The material container is equipped with a continuous material supply system with controlled flow rate. The reactor wall temperature (usually 1100-1400°C) can be regulated by the torch power and by the feeding rate of the material to be treated. The pressure in the supply conveyor is automatically kept higher than the pressure inside the reactor by controlled nitrogen flow to prevent the flow of reactor gases into the material supply system. Wood pellets, polyethylene, plastic waste have been treated. Crushed wood with dimensions up to several mm has been injected into the plasma jet at a location of about 30 cm downstream of the input plasma entrance nozzle at the reactor top. The free plasma jet containing a mixture of argon and steam enters the reactor volume through the nozzle with diameter of 40 mm in the wall. It is partially gasified during its flight within the jet. The non-gasified part of the wood falls to the bottom of the reactor where it is gasified in the hot gas flow. The exit tube for exhaust gas is located at the upper part of the reactor, forcing the produced gases to pass through the zone of high temperature within the plasma jet or close to it (mixed flow reactor). Furthermore, due to its high temperature this plasma jet is a very intensive source of UV radiation and hence has a strong gas cleaning effect. Additional gases (like CO₂ and oxygen) to control the reactor atmosphere can be injected at three positions in the upper part of the reactor. The gas produced in the reactor flows through a connecting tube to the cylindrical quenching chamber. At the output of the quenching chamber the gas has a temperature of 300 °C, and flows into a combustion chamber where it is combusted in a flow of air. The torch generates an oxygen-hydrogen-argon plasma jet with extremely high plasma enthalpy and temperature, and is attached at the top of the reactor. The anode of the torch consists of a rotating water-cooled disc, which is positioned outside the arc chamber downstream of the torch exit nozzle. Additional argon has been supplied into the chamber at the location of the mounted torch to protect the anode from the flow of reaction gases. The measuring system includes monitoring of plasma torch operation parameters, temperatures in several positions inside the reactor and calorimetric measurements on cooling water loops.

The results of experiments with gasification of crushed wood in argon/steam plasma demonstrate the complete gasification of wood with production of syngas with high content of hydrogen (28 - 46% vol.) and CO (44 - 68%). In spite of the low plasma flow rate and the constricted plasma jet, homogeneous heating in the reactor as well as efficient mixing of the treated material with plasma and intensive energy transfer are observed. The flow within the reactor is almost completely controlled by gasification of the material as the flow rate of syngas coming from gasification is up to hundred times higher than the flow rate of plasma from the torch. The calorific value of the produced syngas is of the order of 2.5 times higher than the torch power. The process can act as an energy storage whereby electrical energy is converted into plasma energy and then stored as chemical energy of the produced syngas. The content of complex hydrocarbons or tar is below 10 mg/Nm³.
Figure 1. Schematic diagram of the experimental reactor for plasma pyrolysis & gasification

It can be concluded that homogeneous heating of the reactor volume and proper mixing of plasma with treated material occur in spite of the low plasma mass flow rate and the constricted plasma jet. The mixing is more intensive at higher feeding rates. The conditions within the reactor ensure complete destruction of the tested substance. Furthermore, a novel and attractive procedure of molecular dissociation of CO$_2$ by utilizing it as oxidizing medium in the reactor has been demonstrated. No effect of arc power on gas composition and flow rate is observed for tested feeding rates up to 50 kg/h. It can be concluded that the maximum possible feeding rate at given power has not been reached. The treatment of feedstocks is being optimized with respect to the quality of the synthetic gas according to criteria determined by the end use such as: maximum energy content of the syngas for electricity or heat production (*thermal conversion*), or the production or recovery of a valuable by-product from the syngas such as hydrogen and methanol or other biofuels from a very broad range of second generation biomass feedstock (*chemical conversion*) [4]. Apart from purely economic factors, other factors have to be taken into account such as greenhouse gas and mass & energy balances, the potential competition with food production and the impact of biomass production on the environment. The co-production of fuels, heat & power and co-products enhances the overall economy and competitiveness of biofuels.

4. Destruction of toxic organic compounds

The most widely used treatment of toxic organic waste is thermal processing, e.g. direct combustion in industrial furnaces and boilers. This pertains mostly to liquid and solid waste with moderate and high calorific value and a minimum content of halogens. However, the combustion conditions do not always match the necessary parameters for complete combustion of organic waste, leading to large emissions of harmful substances into the atmosphere.

An alternative method is based on thermal plasma technology [5]. The use of plasma torches with mean temperatures of order 5000 K allows to efficiently destroy complex organic compounds with very high speed and high degree of conversion. This can occur in the absence of oxygen, providing the opportunity to successfully carry out plasma pyrolysis reactions which in some cases has advantages in comparison with combustion. A plasma reactor with three plasmatrons (total power 160 kW) was developed and built at the A.V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus in Minsk. This reactor
can use plasma forming gases of different composition and is easily tunable for processing various types of toxic organic waste, including Persistent Organic Pollutants (POPs). The heart of the plasma-chemical reactor is a three-jet mixing chamber using air as plasma forming gas (3-6 g/s). The processing is characterized by highly turbulent plasma flow in the three-jet mixing chamber, ensuring high-intensity mixing of the plasma flow and the waste. The high temperature leads to a complete degassing of the inorganic ash residue. Shock cooling (quenching) is used to avoid the formation of secondary toxic products. Acids are neutralized in the alkaline environment of a wet filter. The tests showed that the thermal efficiency of the plasma torch in the temperature range 3000-5000 K is 60-70%. The use of different plasma forming gases allows to control the process parameters and to achieve a high level of toxic substance processing.

5. Low and intermediate level radioactive waste vitrification

Incineration of radioactive waste in furnaces leads to the generation of large amounts of contaminated waste gases and toxic fly ash. An alternative process of direct incineration of radioactive waste is plasma technology. The use of electric-arc plasma with mean temperatures 2000 – 8000 K allows to efficiently destroy organic compounds with very high speeds and high degree of conversion. The main advantages of plasma vitrification of low and intermediate level radioactive waste are:

- A single process can treat the as-received waste; no need of costly sorting infrastructure
- No need for other treatment facilities for non-burnable waste
- The process fulfils ALARA principles: eliminating risks for personnel; limitation of dose exposure
- Volume reduction factor (VRF) mixture organic/inorganic; 6; VRF primarily organic; 80
- Environmentally friendly process: no fossil fuel, less production of flue gases
- High temperature and energy density lead to high specific productivity
- Small dimensions of plasma reactors and furnaces
- Only 10 % air needed, decreasing energy input and increasing effectiveness of exhaust gas cleaning
- Solid products are chemically stable with low rate of leaching and suitable for long time storage
- Can be used for reconditioning historical waste which does not comply with actual criteria.

A plasma reactor with a DC plasma torch of 80kW and a capacity of up to 30 kg/h for thermal processing of low and intermediate level waste of mixed morphology was designed and manufactured at the A.V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus in Minsk. The equipment offers a method of plasma-pyrolytic environmentally friendly conversion of waste and receiving conditioned products in a single stage, reducing the volume of conditioned waste significantly in a form that suits long-term storage.

References
[1] Tendler M, P. Rutberg P and Van Oost G 2005 Plasma based treatment and energy production Plasma Physics and Controlled Fusion 47 A219
[2] Hrabovsky M et al 2006 Properties of hybrid water/gas DC arc plasma torch, IEEE Trans. on Plasma Science 34, Issue 4, Part 3, 156
[3] Van Oost G et al 2006 Pyrolysis of waste using a hybrid argon- water stabilized torch Vacuum 80 1132 and references therein
[4] G. Van Oost et al 2009 Pyrolysis/gasification of biomass for synthetic fuel production using a hybrid gas-water stabilized plasma torch Vacuum 83 209 and references therein
[5] G. Van Oost et al 2013 Destruction of toxic organic compounds in a plasma-chemical reactor Vacuum 88 165 and references therein
[6] Kvedchyn I, Sauchyn V and Van Oost G 2014 Low and intermediate level radioactive waste vitrification in plasma reactor Proc. 9th International Conference on Plasma Assisted Technologies (ICPAT 2014, St. Petersburg)