Plasma for environment

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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. It allows the conversion of organic waste into energy or chemical substances as well as the destruction of toxic organic compounds 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

Human activity is associated with the permanent emergence of a very wide range of waste streams. The most widely used treatment is thermal processing such as incineration. However, the combustion conditions do not always match those parameters that are necessary for complete combustion of organic waste, which leads to large emissions of harmful substances into the atmosphere. As a result, exhaust gases may contain dangerous products of incomplete chemical burning.

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. The driving force is to give priority to environmental quality at affordable cost, and to contribute to sustainable development. Thus, the investigation of ways to increase the efficiency of the plasma based treatment processes is very important. In most industrialized countries, integrated solid waste management is mainly governed by the so-called “Ladder of Lansink”. This ladder specifies a generally accepted hierarchy of preferred methods for dealing with waste. The highest rung is occupied by waste prevention, followed (in that order) by re-use (of the object as it is), recycling (material re-use without loss of quality) and down-cycling (material re-use with loss of quality). A still lower rung is the energy recuperation from waste (by incineration, gasification or pyrolysis), followed by incineration and/or destruction of waste without energy recuperation while the least preferred option is landfill.

An alternative waste treatment process is based on thermal plasma technology [1]. Plasmas have a great potential to contribute to sustainable development. The present paper deals with the use of thermal plasmas for the treatment of waste. The use of electric-arc plasma (plasma torches or plasmatrons) with mean temperatures of order 5000 K allows to effectively carry out the efficient destruction of organic compounds into atoms and ions with very high speed and a high degree of conversion. In addition, the destruction of complex compounds in the plasma is very efficient. The amount of gaseous products is much smaller than that of products resulting from traditional
technologies based on combustion. This leads to a drastic reduction in the amount of flue gas to be cleaned. Plasma technology 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. It allows the conversion of organic waste into energy or chemical substances in a scenario that for each specific type of waste can be considered optimal, both in terms of energy efficiency and environmental safety. Efficient automation of the processes is possible since for varying waste stream parameters the plasma generators can be easily feedback controlled, and there is a possibility to change the temperature and enthalpy of the plasma flow in real time and, if necessary, the chemical composition of the plasma can be adjusted. Furthermore, the low inertia of the process minimizes the risk of harmful emissions in case of emergency, with the ability to quickly stop the process.

*Thermal plasma pyrolysis and vitrification is a dual simultaneous disintegration process.* The feedstock is treated by thermal plasma in a reactor chamber, whereby organic components are converted into a synthetic gas of high calorific value, and inorganic components are converted into a non-leachable vitrified lava. The treatment of feedstocks is being optimized with respect to the quality of the synthetic gas according to criteria determined by the end use. These criteria can be: the 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 methanol, respectively hydrogen for fuel cells (*chemical conversion*).

The fact that thermal plasma technology is characterized by a high energy consumption has hindered its further development for industrial applications. 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.

Two examples of thermal plasma treatment of waste will be 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 medium 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 torches 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 high 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
The gasification of biomass to produce synthesis gas (syngas) offers an alternative to fossil fuels. 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, H$_2$, CO$_2$ and H$_2$O(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 pure pyrolysis in the absence of oxygen. In this process all energy needed for gasification comes from the plasma, and no energy for decomposition is produced by combustion. 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, CO$_2$ 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 if air or nitrogen are used as plasma gases. 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 H$_2$O 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%). Several types of gas torches will also be used for biomass gasification on this reactor.

The experimental plasma-chemical reactor (see Figure 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. To prevent destruction of the ceramic insulation, prior to experiments the reactor is preheated for 24 hours to about 950 °C and further to the operational temperature by the plasma torch at a power level of 110 kW. 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 then the pressure inside the reactor by controlled nitrogen flow to prevent the flow of reactor gases into the material supply system. Crushed wood with dimensions up to several mm has been injected into the plasma jet at a location of about 30cm downstream of the input plasma entrance nozzle at the reactor top. 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 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 with length 2m. 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.

**Figure 1.** Schematic diagram of the experimental reactor for plasma pyrolysis & gasification.
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. The anode of the torch is thus located inside the reactor and separated from the reactor volume by a water-cooled wall. 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 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. 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 temperature of the inner wall of the reactor is measured in six positions by thermocouples. The flow rate of reaction gas is measured using a Pitot tube flow meter. The gas temperature is measured at the input and output of the quenching chamber by thermocouples. The composition of the produced gas is measured at the output of reactor before the gas enters the quenching chamber. The main gas analysis is made by a quadrupole mass spectrometer Balzers QMS 200. Other analyses of the composition of the produced syngas and the content of tar are by means of mass spectroscopy with cryofocusing, gas and liquid chromatography and Fourier transform infrared spectroscopy (FTIR).

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 and carbon monoxide. 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. Depending on operational conditions, the main components of produced syngas are hydrogen (28 - 46% vol.), CO (44 - 68%), CO$_2$ (2 - 8%) and Ar (0.2 - 8%). The content of complex hydrocarbons or tar is below 10 mg/Nm$^3$. The composition of the reaction products resulting from the pyrolysis of crushed wood is given in Figure 2. Furthermore, wood pellets, polyethylene and plastic waste have also been treated.

![Figure 2](image-url). Gasification of wood in a steam/Ar plasma with addition of CO$_2$ and oxygen: composition of products of reaction as a function of the temperature in the reactor. Wood feeding rate 47 kg/h; humidity 6.5%; water plasma flow rate 18g/min; argon 13.6 slm (standard liter per minute); CO$_2$ 115 slm, O$_2$ 30 slm.
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 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\textsubscript{2} by utilizing it as oxidizing medium in the reactor has been demonstrated and will be optimized. 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 aim is also to demonstrate the economical viability, environmental performance and safety of biofuels and hydrogen produced from syngas resulting from the plasma-thermochemical gasification of a very broad range of second generation biomass feedstock (incl. the biodegradable fraction of waste) using several types of plasma torches and possible combinations of torches [4]. The plasma technology will be further optimized. Plasma-assisted combustion of biomass will also be investigated in existing (classical) biomass gasification installations. 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 will enhance the overall economy and competitiveness of biofuels. The possibility of reforming of CO\textsubscript{2} is also very attractive.

4. Destruction of toxic organic compounds

The most widely used treatment of toxic organic waste is thermal processing. Common practice is 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 in these furnaces and boilers do not always match the parameters that are necessary for complete combustion of organic waste, leading to large emissions of harmful substances into the atmosphere. As a result, exhaust gases may contain dangerous products of incomplete chemical burning. This is due to the fact that the process of neutralization of organic waste by thermal methods is carried out at temperatures sensitive to the formation of other harmful compounds. The combustion of chloro-organics at insufficiently high temperatures, in addition to nitrogen oxides and carbon monoxide, may lead to the formation of phosgene, dibenzofurans, dioxins, furans, polychlorinated benzopyrene, polyaromatic hydrocarbons, oxides of sulfur, soot and other very toxic products in quantities exceeding the maximum permissible concentration, in addition to nitrogen oxides and carbon monoxide. Chloro-organic waste processing is a serious problem. The amount of waste production and consumption that contains chloro-organic compounds is millions of tons. They include end-of-life products of chloro-organic polymers, used chlorinated hydrocarbon solvents (including additives), dielectrics (polychlorinated biphenyls) unusable pesticides, and residues of chloro-organic production. Dumping chloro-organic waste at landfills and disposal should be completely excluded because of their poor biodegradability and the possibility of oxidation of many of them by air oxygen under the influence of sunlight to form secondary toxic products (phosgene, etc.).

An alternative method to treat toxic organic waste is based on thermal plasma technology [5]. The use of electric-arc plasma with mean temperatures of order 5000 K allows to effectively carry out the destruction of organic compounds into atoms and ions with very high speeds and a high degree of conversion. In addition, the destruction of complex compounds in the plasma is very efficient and 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 three-jet plasma reactor with electric-arc plasma generators with a total capacity of 200 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 waste belonging to the group of Persistent Organic Pollutants (POPs). The heart of the plasma-chemical reactor is a three-jet mixing chamber which is equipped with three electric-arc plasma torches (power 50 kW; thermal
efficiency up to 70%; plasma forming gas air; plasma forming gas consumption 3-6 g/s). The processing is characterized by highly turbulent plasma flow, which is formed in the three-jet mixing chamber, thus ensuring high-intensity mixing of the plasma flow and the substances to be treated. The high temperature in the reactor leads to a complete degassing of the inorganic ash residue. A shock cooling (quenching) module is used to avoid the formation of secondary toxic products. Acids are neutralized in the alkaline environment of a wet filter. An Ion Mobility Spectrometer RAID S2 is used for the detection of chemical agents in the air to control the exhaust gas composition and to prevent environmental disasters.

The tests showed that the thermal efficiency of the plasma torch in the temperature range 3000-5000 K is 60-70%. By using different composition of plasma forming gas the parameters of the medium inside the reactor can be controlled to achieve high level of toxic substance processing. Based on the results of the experiments, a pilot plant is being developed for the safe plasma-chemical processing of pesticides and toxic waste.

References
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