Applications of Thermal Plasma Waste Treatment

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Contributor: Guido Van Oost

Non-thermal as well as thermal plasmas are used for the processing of materials and waste. Thermal (hot) plasmas are characterized by their high energy density and by the equal temperatures of the electrons and the heavy particles, i.e., thermal plasmas are in local thermodynamic equilibrium. Non-thermal plasmas (also called cold plasmas), on the other hand, are non-equilibrium ionized gases, which are characterized by lower energy densities and by the large difference between the electron temperature and the temperature of the heavy particles.

thermal plasmas   waste treatment   problematic waste

1. Thermal Plasma Waste Treatment

Thermal plasmas [1] offer unique advantages such as high temperatures in the range of 5000 to 50,000 K, high energy density, high energy transfer rate and extremely low reaction times for chemical reactions. Different types of plasma sources are used in various plasma processing technologies. Arc discharges create a high-density, high-temperature region between the electrodes. If the gas flow in the electrode gap is high enough, the plasma jet extends beyond one of the electrodes, transporting the plasma energy to the reaction region. A plasma torch, also known as a plasmatron, is a device that generates a directed stream of thermal plasma from the nozzle. An overview is given in [1]. The primary source of electricity for plasma torches can be direct current (DC), mains frequency (50 Hz) alternating current (AC), radio frequency (RF) alternating current, or microwaves. Other features of plasma torches include arc stabilization mechanism, plasma gas, flow type, and electrode geometry and cooling. Thermal plasmas used in waste treatment and material gasification systems are commonly produced in DC or AC electric arc discharges operating in a non- transferred mode (both electrodes are parts of the torch, and the plasma jet exits the torch through an exit nozzle). The main problem of arc discharges is erosion of electrodes and nozzles. The lifetime of inductively coupled RF discharges and microwave discharges, which operate without electrodes, is higher, but the complexity and cost of power supplies are the main limitation for high-power systems.

Thermal plasmas (produced in plasma torches) offer an alternative and superior solution for the treatment of waste streams. Organic components are converted into a calorific syngas (a mixture of mainly hydrogen and carbon monoxide), while the inorganic components can be converted into a slag directly in the process. Due to the unique property of strongly intensifying the energy content of the process gas, plasma torches offer very clear advantages over traditional combustion which relies on the energy content of the waste as a heat source. In the plasma torch, the process heat is supplied directly by heat transfer through the electric arc discharge. The use of electrical energy also enables the allothermic mode of operation, reduces the required oxygen supply (which is normally injected as air along with a lot of nitrogen, increasing the volume of the waste gas to be treated) and allows better control of the chemical processes. Another advantage is the ability to produce a syngas free of nitrogen by providing exactly the amount of gasifier (e.g., CO_2) to allow for carbon volatilization or solid carbon production.

2. Applications of Thermal Plasma Waste Treatment

In recent years the number of applications of thermal plasmas has increased significantly. Basic research in the 1990s led to major advances in understanding the fundamental phenomena involved and to a renewed interest in the use of thermal plasmas in materials processing and the environmentally friendly treatment of waste streams [2][3]. The stricter environmental legislation on the processing of waste streams and the limitations of conventional technologies make plasma technologies increasingly attractive. *Priority is given to environmental quality at affordable costs* and to the use of innovative thermochemical conversion technologies (gasification and pyrolysis) to *contribute to sustainable development and circular economy in which waste is managed as a resource.*

In Comparison with Conventional Thermal Treatment, the Main Advantages of Thermal Plasmas Treatment of Waste Streams Are:

- Much higher temperatures. The temperature inside the reactor can be controlled by the torch power, waste feed rate, and plasma gas flow rate;
- Highly reactive environment (reactive species such as atomic oxygen and hydrogen) and reducing atmosphere in the gasification process resulting in reduced NO_x emissions;
- Short residence times and high throughput due to the high energy density of the plasma and the high heat transfer efficiency;
- Lower amount of plasma gas per unit of calorific power than of the gas flow in conventional technologies. Therefore, there is less loss of the energy necessary to bring the gas to the reaction temperature, and the amount of gas diluting the syngas produced is lower;
- Deep breakdown of waste into simple compounds, greatly simplifying the cleanup of harmful impurities;
- Possibility of joint treatment of different types of waste without pre-sorting, which is particularly important for the treatment of biomedical waste and other non-sorted toxic waste;
- Because high and homogeneous temperatures can be easily maintained throughout the reactor volume, the production of higher hydrocarbons, tar and other complex molecules is significantly reduced compared to combustion;
- Gasification at high temperature and rapid cooling of the synthesis gas prevent the formation of dioxins and furans (the most dangerous toxic substances);

- Low thermal inertia and easy feedback control. Possibility of quickly adapting the process by modifying the flow rate of the oxidant (air, steam or other plasma gas) and the power of the plasma torches. Ability to create the desired gas atmosphere. In an emergency a quick shutdown of the process is possible;

- Significant reduction in the volume of flue gases and, therefore, the load on the gas cleaning system, and less entrainment of dispersed particles;

- Smaller installations due to the high energy density of the plasma, the lower gas flow rates and the reduced flue gas volume;

- The heat source is electricity rather than the energy released during combustion and is, therefore, independent of the waste being processed. This provides rapid and flexible process control and more possibilities in process chemistry, including the capacity to generate valuable by-products. Easy temperature control in the reactor is made possible by changing the power of the plasma torches and the feed rate of waste and added gases;

- Optimal control of the composition of the final product in stable form. Possibility of obtaining a more calorific and cleaner synthesis gas from the organic part of the waste, which is not contaminated by the typical by-products of conventional gasification (in particular, tar);

- Vitrification of combustion ashes and production of vitrified slag usable as construction material;

- Recovery of value-added products (metals) from the slag.

Plasma gasification is a promising method for treating *solid and liquid combustible waste* [2][4]. Plasma methods have been used successfully in industry for decades. Reviews are presented in [2][3]. There are not many examples of plasma gasification on a commercial scale, but there are a large number of laboratory studies and pilot plants whose researchers are unanimous in their opinion on the prospects of gasification, combustible waste plasma and the uniqueness of plasma technologies. Three examples of thermal plasma treatment of waste (*biomass, toxic organic waste and sewage sludge*) are presented below from the personal experience of the researchers.

Conventional *biomass gasification* technologies are based on the reaction between limited amounts of air or oxygen and solid or liquid carbonaceous material (containing mainly chemically bonded carbon, hydrogen and oxygen). The exothermic reactions release sufficient heat from the calorific value of the biomass for the production of a primary gaseous product containing mainly CO, H_2, CO_2 and H_2O(g) and a small amount of higher hydrocarbons. The major problems of conventional biomass gasification are the low heating value of the syngas and the production of tar consisting of complex molecules of hydrocarbons created during the process at low temperature. In thermal plasma gasification (or plasma pyrolysis), the concentration of tar compounds in the produced syngas is much lower if the process is carried out such that the produced gas leaves the reaction zone at high temperatures (>1000 °C). Compared to conventional gasification routes (such as fluidized bed gasification), the synthesis gas produced contains only traces of tar (tens of mg/m^3) [4] compared to tens of g/m^3 with fluidized bed gasification, which enables the cleaning of syngas at temperatures of 100–200 °C without the risk of tar condensation on the filters. Biomass plasma gasification can also act as energy storage whereby electrical energy is transformed into plasma enthalpy and then stored in the produced syngas.

Thermal processing such as incineration is most commonly used for the treatment of *hazardous organic waste* (e.g., pesticides) [5] with medium to high calorific value and low halogen content. However, the often-incomplete chemical combustion of organic waste can lead to dangerous products in the exhaust gases. Indeed, the process of neutralizing organic waste by thermal methods is carried out at temperatures conducive to the formation of other harmful compounds. The use of arc plasma with average temperatures of the order of 5000 K enables the decomposition of complex organic compounds into atoms and ions at very high speeds and high conversion rate. In addition, this process can take place in the absence of oxygen, offering the possibility of carrying out plasma pyrolysis, which can have advantages in comparison with combustion.

Municipal *sewage sludge* is rich in both organic matter and phosphorus. On the other hand, it contains organic pollutants and heavy metals. From 2020 the microbiological criteria for the application of sludge in the soil are tightened, and it is likely that landfilling will be banned completely in the EU from 2024 [6]. Phosphorus is on the list of critical EU raw materials as an important nutrient, and, in some European countries, it is already legally enforceable that phosphorus must be extracted from sewage sludge. At present, however, this acquisition is hampered by the economic barrier created by the high cost of recovered phosphorus, which cannot compete with the price of the primary raw material. However, the latter is gradually increasing, which can be seen as an opportunity to store the ash from the combustion of sludge for later phosphorus recovery.

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