Researches on energy conversion of municipal waste by plasma decomposition for energy-efficiency in civil engineering

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Abstract. This paper presents the research, technologies and testing equipment developed for the energy plasma conversion of municipal waste in order to enhance energy-efficiency in the civil engineering domain. The purpose of this work is the environmentally friendly improving the efficiency of waste conversion processes by using controlled plasma decomposition reactors developed by the authors, which generate syngas, electrical and thermal energy which can be used in civil engineering.

1. Introduction and study objectives

In 1960 the world population was 3 billion, in 2019 is over 7.7 billion and it is expected to be 8.1 billion in 2025 [1]. The growth of the global population mixed with economic evolution led to rapid urbanization and industrialization, which automatically changed the consumption pattern of the population that finally head up to the rapid increase of Municipal Solid Waste (MSW) at alarming rates [5, 16, 24]. A lot of countries adopted Waste To Energy (WTE) technologies for efficient management of large quantities of waste to produce energy [5, 6]. A foresight made by the International Renewable Energy Agency revealed that the world has the potential of generating approximately 13 GigaWatt of energy from the WTE sector alone [2, 3, 7]. WTE technologies have been considerably modernized in the last years, in 2012, the USA alone generated 14.5 million MWh of electricity from 84 WTE facilities [4].

The general principles of waste management are: the waste prevention to reduce emissions, the reduction of hazardous substances in material streams and the increase resource efficiency, the preparation for reuse that involves checking, cleaning, or recovery by which products or components of products, which have became waste could be prepared for reuse, and, also, the energy recovery from waste and other recovery activities. The energy production from waste (WTE) involves burning waste and using energy content of the waste to produce electricity or to obtain heat and power, heat is used for various services. The disposal of waste in landfills in ecological storage is the least desirable option in waste management hierarchy having the most negative effects on environment and human health [8, 9, 10, 21, 25, 26].

Classic technologies for the energetic processing and recovery of recyclable materials from municipal waste are [11, 23]:

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a) Selective collection/sorting and recycling followed by controlled storage of waste in green
landfills, which means a sum of technologies for the reuse of materials obtained from waste, to become
the raw material for various economic processes. This is characterized by [27]:
- solid wastes are obtained without the energetic contribution and with negative influence on the
  environment;
- a mixture of combustible gases (CH₄, CO, H₂, C) is obtained with low purity, low calorific value
  and a high percentage of dangerous accompanying gases [5, 12];
- the technological installations are voluminous, and they require large areas for installation, they
  are high energy consumption, the duration of the technological process is very high and the
  volume of fuel gas obtained is small.

b) Thermochemical processes which are characterized by:
- direct combustion - it produces thermal energy, a large volume of ash and inert materials, a high
  percentage of dangerous gases with a negative impact on the environment;
- gasification - obtaining a gas mixture of H₂, CO, CH₄ with reduced calorific value, a high
  volume of inert materials;
- pyrolysis/incineration - the thermal process that takes place in the absence of oxygen, produces
  combustible gases and thermal energy (CH₄, CO, H₂, C obtained from the decomposition of
  biological material at 700 °C according to the chemical reaction C₆H₁₀O₂ → CH₄ + 2CO + 3H₂O
  + 3C [5].

2. Material and methods
Modern technologies for energy recovery of municipal waste as a renewable energy source are
represented by Plasma gasification, which is a V - generation technology through [13]:
- a mixture of combustible gases H₂, CO, CH₃, CH₄ (syngas) is produced with high purity
  and calorific value [14];
- a vitrified mineral waste with a volume between 5-10% with minimal impact on the
  environment, hardness and properties similar to ceramic materials (use in construction)
  [15][28];
- the resulted syngas can be used to obtain raw materials in the field of the chemical industry,
  fuels or directly converted into electricity and heat [16];
- the technological installations are compact, and the technological processes are carried out in
  short periods of time, while the volume of fuel gas obtained is high [16].

![Figure 1. Comparative analysis between plasma gasification and pyrolysis/incineration.](image)

These modern technologies are defined as:
a) Westinghouse plasma technology - plants use plasma torches on gas, equipment is high working temperatures which are about 4,000 °C, electricity consumption is high, processed waste requires humidity reduction, syngas obtained has a high percentage (5-10%) of gases dangerous for the environment with low calorific power, the volume of inert material obtained is high [17, 18].

b) Plasma hydrogen technology obtained by dissociation of water in plasma jet - the installations are compact of small size, with working temperatures between 10,000-20,000 °C, do not require drying of waste, the syngas obtained has a high percentage of combustible gases $\text{H}_2 \approx 50-55\%$, $\text{CO} \approx 20-25\%$, $\text{CO}_2 \approx 15\%$, and accompanying gases are around 1-5% with minimal environmental impact [17, 18, 19].

The following layout (figure 2) describes the overall configuration and the main components of a new technological developed installation, and the prototype is a result of a scientific research project. The necessary utilities are:

- power grid with an installed power of 210 kW at 380 V, 50 Hz,
- running water with a flow of at least 2 mc/h.

![Figure 2](image_url)

**Figure 2.** The schematic diagram of equipment for hydrogen plasma conversion of municipal waste.

The main objective of the research was the design of an eco-innovative plasma-based technology for the recovery of waste as a renewable energy source, improvement of the technical and economic performance of the plasma installation for the waste processing by upgrading some components of the system (plasmas, adaptive thermal conduction processes from the plasma reactor enclosure, plasma gas purification system), and optimization of the syngas production technology by controlling the plasma conversion of waste depending on the results obtained from the modeling and simulation of thermo-chemical processes with the help of Chemcad specialized software [20].

The new technological system converts into synthetic gas any solid municipal waste using high-temperature plasma technology and hydrogen technology. Synthesis gas can be used to generate energy, liquid fuels or other sustainable energy sources. It operates in a continuous mode using as a source of energy only to initiate the process of the electricity network, minimizing the energy consumption by means of its own cogeneration system. The heat produced in the process is recovered at various points.
in the plant and is used to obtain the heating agent needed to supply an external district heating system [20].

Electricity produced through another cogeneration module may be supplied to a local power grid or national system [22].

The designed installation has the following technical features, presented in table 1:

| Entry | Exit |
|-------|------|
| raw material (organic substance) | slag (vitrified) = 8.2 kg/h |
| = 410 kg/h humidity = 35% | inert material = 141.8 kg/h |
| - caloric power = 13.9 Mj/kg | residual heat of 0.007 MWt |
| - water as vapor = 65 kg/h | singas = 325 kg/h, |
| slag (vitrified) = 8.2 kg/h | which represents 1,533 MWt chemical energy with 10.87 Mj/m³ calorific value |
| inert material = 141.8 kg/h | residual heat of 0.007 MWt |
| water as vapor = 65 kg/h | residual heat of 0.007 MWt |

Electricity produced through another cogeneration module may be supplied to a local power grid or national system [22].

The designed installation has the following technical features, presented in table 1:

Table 1. Raw - energy balance

| Entry | Exit |
|-------|------|
| Entry | Exit |
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| inert material = 141.8 kg/h | residual heat of 0.007 MWt |
| water as vapor = 65 kg/h | residual heat of 0.007 MWt |

Table 2. Energy balance

| Step 1 - energy conversion | Step 2 - energy conversion |
|---------------------------|---------------------------|
| The cogeneration system with a single-turbine and a 34% efficiency generator produces 0.521 MWe/h of which: 0.200 MWe/h is for the operation of plasma torches, separator, and control system. | The steam turbine receives 0.74 MWt at 90% efficiency, operates an electric generator with a 30% efficiency that produces 0.222 MWe/h. |
| - plasma torque = 0.142 MWe/h | Thermal energy recovered: |
| - water / solid separator = 0.050 MWe/h | - in the single wash and neutralization module = 0.231 MWt |
| - organic substance carrier in the reactor = 0.005 MWe/h | - boiler 1 (steam turbine) = 0.273 MWt of which 0.143 MWt for torches and plasma reactor |
| - measurement and control systems = 0.003 MWe/h | - boiler 2 (heat / steam exchanger recovered from the steam turbine) = 0.443 MWt |

Electricity available to internal consumers or the public grid:

0.521 MWe + 0.222 MWe = 0.743 MWe;

of which 0.200 MWe consumed for the operation of the plasma installation and 0.543 MWe for sending in the network.

Total thermal energy recovered:

0.231 MWt + 0.273 MWt + 0.443 MWt = 0.947 MWt

of which are available for external heating to consumers = 0.804 MWt

These technical parameters were compared with the parameters resulting from the modeling and simulation of thermo-chemical processes of plasma waste processing with Chemcad resulting in a small variation between them. Figure 3 presents the modeling and simulation of the main reactor with plasma on hydrogen.

The sludge from in the designed installation is largely eliminated, the resulting vitrified material is inert and in minimal quantity, easy to recycle with the possibility of recovering heavy metals.

The installation allows the reduction of greenhouse gas emissions:

- reduction up to 40% CO₂ and 100% CH₄, efficient filtration without toxic gas emissions;
- reduction of the quantity of SO₂, SO₃ and NOₓ (acid rain factors);
- reduction of dioxins and furans.
The average operating time of the plasmas is approx. 3,000 h (24 h/day) maintenance requires the replacement of anodes and cathodes from the plasma construction (replacement is a simple assumption to replace compact equipment without removing the reactor). The installation works completely automated, online, from a distance without the intervention of an operator.

![Simulation of the hot gas flow in the plasma reactor.](image)

**Figure 3.** Modeling and simulation of the main reactor with plasma on hydrogen

3. **Conclusions**

The goal of the paper was to describe the efficiency of waste conversion processes by using controlled plasma decomposition reactors developed in the research, which generate syngas, electrical and thermal energy that can be used in civil engineering as treatment of a large variety of wastes (municipal solid wastes, construction wastes, heavy oil, used car tires, medical wastes etc).

By using the plasma technologies different environmental problems can be resolved:

- reducing substantially the waste going to landfill sites;
- reducing CO₂ emissions;
- reducing the usage of fossil fuels;
- safe destruction of medical and numerous hazardous waste.
Beside syngas and heat, another important product of the plasma decomposition process is vitrified slag, which potentially can be used in the construction sector.

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