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From waste to electricity through integrated plasma gasification/fuel cell (IPGFC) system

G. Galeno [a], M. Minutillo [b], A. Perna [a,*]

[a] Department of Industrial Engineering, University of Cassino, Via G. Di Biasio 43, Cassino, Italy
[b] Department of Technology, University of Naples "Parthenope", Centro Direzionale, Naples, Italy

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ABSTRACT

The waste management is become a very crucial issue in many countries, due to the ever-increasing amount of waste material, both domiciliary and industrial, generated.
The main strategies for the waste management are the increase of material recovery (MR), which can reduce the landfill disposal, the improvement of energy recovery (ER) from waste and the minimization of the environmental impact.
These two last objectives can be achieved by introducing a novel technology for waste treatment based on a plasma torch gasification system integrated with a high efficiency energy conversion system, such as combined cycle power plant or high-temperature fuel cells.
This work aims to evaluate the performance of an Integrated Plasma Gasification/Fuel Cell system (IPGFC) in order to establish its energy suitability and environmental feature.
The performance analysis of this system has been carried out by using a numerical model properly defined and implemented in Aspen Plus™ code environment. The model is based on the combination of a thermochemical model of the plasma gasification unit, previously developed by the authors (the so-called EquiPlasmaJet model), and an electrochemical model for the SOFC fuel cell stack simulation.
The EPJ model has been employed to predict the syngas composition and the energy balance of an RDF (Refuse Derived Fuel) plasma arc gasifier (that uses air as plasma gas), whereas the SOFC electrochemical model, that is a system-level model, has allowed to forecast the stack performance in terms of electrical power and efficiency.
Results point out that the IPGFC system is able to produce a net power of 4.2 MW per kg of RDF with an electric efficiency of about 33%. This efficiency is high in comparison with those reached by conventional technologies based on RDF incineration (20%).

1. Introduction

The waste management is become a very crucial issue in many countries, due to the ever- increasing amount of waste material, both domiciliary and industrial, generated.

The main strategies for the waste management are the increase of material recovery (MR), which can reduce the landfill disposal and the improvement of energy recovery (ER) from waste.

Conventional technologies for the energy recovery from waste are based on the incineration process and pyrolysis or gasification processes [1–9]. While both pyrolysis and gasification are feasible technologies to handle municipal waste, commercial applications of these technologies have been limited.

* *Corresponding author*. Tel.: +39 07762993634; fax: +39 07762993886.
E-mail addresses: g.galeno@unicas.it (G. Galeno), mariagiovanna.minutillo@uniparthenope.it (M. Minutillo), perna@unicas.it (A. Perna).
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Nomenclature

EPJ	EquiPlasmaJet
IPGCC	Integrated Plasma Gasification/Combined Cycle
IPGFC	Integrated Plasma Gasification/Fuel Cell
LHV	Lower Heating Value, kJ/kg
RDF	Refuse Derived Fuel
P_e	Net Power, kW
η_{PG}	Plasma gasification efficiency
η_{IPGFC}	Electric efficiency of IPGFC system
S/C	Steam to carbon ratio at the pre-reforming reactor
U_f	Fuel utilization factor
U_{Air}	Air utilization factor
E^0	Ideal voltage for hydrogen oxidation at ambient pressure, V
V_{cell}	Cell voltage, V
I_{cell}	Cell current, A
$I_{L,cat}$	Cathode limiting current, A
Q_{cell}	Thermal power, kW
F	Faraday constant, 96485 C/mol
R	Universal gas constant, 8.314 J/molK
T_{cell}	Cell operating temperature, K
p	Ambient pressure, Pa
p_i	Partial pressure of species “i”
n	Number of electrons
N	Number of elements in which the cell is discretized along the tube axis
J	Single element in the scheme of the tubular cell
$k_{A,an}$	Pre-exponential coefficient of the Anode
$k_{A,cat}$	Pre-exponential coefficient of the Cathode
$E_{A,an}$	Anodic activation energy, J/mol
$E_{A,cat}$	Cathodic activation energy, J/mol
A_i	Area of each section of the cell, m^2
i	Current density, A/m^2
$i_{0,an}$	Anodic exchange current density, A/m^2
$i_{0,cat}$	Cathodic exchange current density, A/m^2
D_{O_2}	Oxygen ordinary diffusion coefficient, m^2/s
β	Electronic transfer coefficient
τ	Tortuosity
ε	Porosity

Recently, an innovative technology, based on the plasma torch gasification, seems to be the most effective and environmentally friendly method for biomass/solid waste treatment and energy utilization [10–19].

The plasma gasification process works at very high temperatures in an oxygen-starved environment and decomposes completely the input waste material into very simple molecules. The organic compounds are thermally decomposed into their constituent elements and converted into a synthesis gas, which mainly consists of hydrogen and carbon monoxide, while the inorganic materials are melted and converted into a dense, inert, non-leachable vitrified slag [10,19].

Therefore, the syngas generated by the plasma gasification is cleaner than that produced by conventional gasification processes [10], due to the high temperatures involved, which allow to broken down all the tars, char and dioxins. However, the production of a very high temperature plasma gas requires an external energy source and thus a high electric consumption of the plasma torches [11,13,19,20].

This drawback can be overcome if the syngas produced by gasification is used as fuel in high efficiency power generation systems, such as combined cycle power plants or high-temperature fuel cells.

In a previous paper [20], the authors focused on conventional technologies for energy generation and thus, they studied the behaviour and the performance of an integrated plasma gasification combined cycle (IPGCC) power plant.

In this paper the integration between the plasma gasification unit and a solid oxide fuel cell (SOFC) system is proposed and the energy suitability of the Integrated Plasma Gasification/Fuel Cell system (IPGFC) is analyzed by means of thermochemical and electrochemical models properly developed.

2. Technology review

This section provides a brief description of plasma torch gasification processes in waste management and introduces the high-temperature fuel cells as a promising power technology for the integration with waste gasification systems.

2.1. *Plasma gasification*

The plasma is created by applying energy to a gas in order to reorganize the electronic structure of the species (atoms, molecules) and to produce excited species and ions. This energy can be thermal, or carried by either an electric current or electromagnetic radiations [21].

Depending on the type of energy supply and the amounts of energy transferred to the plasma, the properties of the plasma change, in terms of electronic density or temperature.

Huang et al. [19] distinguish two main groups of laboratory plasmas, the high temperature or fusion plasmas, in which all species (electrons, ions and neutral species) are in a thermodynamic equilibrium state, and the low-temperature plasmas (a further distinction can be made between the thermal plasmas, in which a quasi-equilibrium state occurs, and the cold plasmas where a non-equilibrium state takes place).

Among all the plasmas processes, the thermal plasmas is the most suitable for waste materials treatment, because the organic compounds, under high temperature conditions, are decomposed into their constituent elements and the inorganic materials (glass, metals, silicates, heavy metals) are melted and converted into a dense, inert, non-leachable vitrified slag [10,16,21].

With respect to the plasma sources for this application field, they can be the arc plasma torches fed by a DC power supply or the metallic torches, in which the plasma is generated by a microwave discharge [21,22]. In an arc plasma torch a DC-ARC discharge provides high energy density and high temperature region between two electrodes and, in the presence of a sufficiently high gas flow, the plasma extends beyond one of the electrodes in the form of a plasma jet [21]. The temperature in the core of the plasma plume can be greater than $3 \cdot 10^4$ °C, whereas in the marginal zones, it