Environmental Engineering and Management Journal

April 2021, Vol. 20, No. 4, 625-634
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

HYDROGEN PLASMA CONVERSION SYSTEM OF MUNICIPAL RECYCLABLE WASTE IN ENERGY

Iulian Cucos[1*], Ion Antonescu[2], Dorina Isopescu[2], Daniel Lepadatu[2], Maria-Oana Agavriloaie[1], Vasile Caunii[1], Vlad-Catalin Cucos[1]

[1]"Gheorghe Asachi" Technical University of Iasi, Faculty of Hydrotechnics, Geodesy & Environmental Engineering, 65 Prof. Dr. Docent D. Mangeron str., 700050 Iasi, Romania
[2]"Gheorghe Asachi" Technical University of Iasi, Faculty of Civil Engineering and Buildings Services, 1 Prof. Dr. Docent D. Mangeron str., 700050 Iasi, Romania

Abstract

The paper presents a synthesis of the main technologies used in municipal waste management, highlighting the main technical characteristics, advantages and disadvantages, the main objective is to improve the technical and economic performance of a plant that uses an innovative and environmentally friendly technology based on hydrogen plasmas for the processing of municipal recyclable waste as a source of renewable and cheap energy.
Plasma gasification is a innovative process, efficient technically and economically, with low impact on the environment and facilities using this technology have reduced carbon footprint. The main equipment of the installation is the assembly consisting of the reactor equipped with plasma torch and the hydrogen plasma gas purification system, powered by power sources controlled by automation devices controlled by advanced control algorithms that act online and anticipate thermal processes and chemicals that occur in the reactor.

Key words: hydrogen, liquid waste, management, plasma, PID and one-step predictive, recycling, systems design, zero emissions

Received: June, 2020; Revised final: February, 2021; Accepted: March, 2021; Published in final edited form: April, 2021

1. Introduction

Integrated municipal waste management involves the following steps (Lombardi et al., 2012; Lombardi et al., 2015; Mukherjee et al., 2020; Ramos et al., 2018; Sogancioglu et al., 2017):

- activities to prevent the production of non-recoverable waste by optimally designing the component parts of industrial products and developing ecological methods for storing agricultural products aims to reduce hazardous gas emissions, reduce hazardous substances in material streams and increase resource efficiency;
- processing certain parts of industrial products by checking, cleaning, or recovery by which products or components of products that have become waste are prepared for reuse;
- energy recovery from waste this activity involves the heat treatment of waste and the use of flue gases for the production of electricity or heat used for various industrial applications or for the thermal heating of buildings or industrial spaces;
- waste disposal in landfills, even if ecological landfills is the least desired option in the waste management hierarchy as these methods have the negative effects on human health and the environment.

The use as energy resource and the recovery of recyclable materials from municipal recyclable waste

* Author to whom all correspondence should be addressed: e-mail: icucos@tuiasi.ro; Phone: +40 0747984527

can be done through the following technologies (Abbasi and Abbasi 2010; Begum et al., 2014; Cucos, 2014; Mazzoni et al., 2017):

a) *selective recycling* followed by the controlled storage of waste in green landfills, is the simplest technology for the reuse of materials obtained from waste, thus becoming raw material for various industrial processes.

b) *Thermo-chemical processes*

1. *direct combustion* characterized by a high percentage of gases with negative impact on the environment, inert materials and high amount of ash, the production only of thermal energy;

2. *the pyrolysis process* is thermal process that takes place in the absence of oxygen and in the presence of substances to control chemical reactions, produces synthesis gas as a mixture of syngas (H_2, CO), CO_2 and a variable percentage of dangerous gases and thermal energy (Matveev et al., 2009; Messerle and Ustimenko, 2007; Messerle et al., 2016; Youngchul et al., 2012; Zhang et al., 2012; Surov et al., 2017);

3. *gasification process* through which syngas is obtained with reduced calorific value, high volume of inert materials. (Couto et al., 2015; Matveev et al, 2008; Matveev, 2016; Messerle et al, 2017; Messerle et al, 2019).

Design of technologies for the conversion of municipal recyclable waste into renewable energy assume (Cucos et al., 2015; Judele et al., 2017):

1. studies on technologies for the conversion of waste into renewable energy;

2. mathematical modeling of the management system in plasma installation and the process of conversion of municipal waste into syngas with the help of plasma torch;

3. mathematical modeling of the plasmatrons and of some main components of the plasma installation.

2. Material and methods

2. 1. Cutting-edge technologies for energy recovery of municipal waste

The main technologies for plasma waste treatment are (Cucos and Munteanu, 2015; Miron et al., 2019):

a) *Westinghouse plasma technology*, processed waste requires humidity reduction, pyrolysis reactors use plasma torches on gas, in equipment working temperatures are about 2,000 – 4,000 ^oC, syngas obtained has a high percentage of dangerous gases with low calorific power and high carbon footprint the volume of inert material obtained is high. (Akishev et al., 2012; Begum et al., 2014; Brunner and Rechberger, 2015; Consonni and Viganò 2012; Matveev and Rosocha, 2010; Ni et al., 2006);

b) *Plasma hydrogen technology,* instalation working temperatures are about 10,000 ^oC, syngas is produced with a high calorific value and purity, with minimal impact on the environment, a vitrified mineral waste and polymetallic nodules with a volume between 5-10% the technological installations are small (Akishev et al., 2012; Farzad et al., 2016; Hofbauer and Materazzi, 2019) the syngas obtained has a high percentage of combustible gases (Moustakas et al., 2008; Matveev and Rosocha, 2010; Rajasekhar et al., 2015) and accompanying gases with minimal environmental impact.

Development of municipal recyclable waste plasma processing plants:

1. realization of the system for controlling the processes in the plasma installation;

2. design of the plasma reactor, automation devices for control process;

3. mathematical modeling of heat transfer from plasma towers to municipal waste and gas flow in the reactor;

4. modeling the control process of the installation, establishing the agreement parameters for thermoregulators classical regulation, PID (predictive integrative derivative) and PID one-step predictive algorithm;

5. simulation of the control process with the Simulink software package (classical, PID and PID one-step predictive regulation) and optimization of parameters for process management;

6. implementation on the real control system of the modeled and simulated installation and experimental validation of the obtained results.

The main advantage of plasma-based hydrogen technology is that hydrogen plasma can carry high energy in small plasma volumes, a large volume of hydrogen is a component of the syngas with a very high calorific value, which makes its usage in the plasma torch more effective than commonly used air torches, no nitrogen compounds appear as waste gases.

2.2. Plasma gasification technology for recycling municipal waste

Plasma gasification is a V - generation technology through (Akishev et al., 2012; Matveev and Rosocha, 2010; Messerle et al., 2018; Ni et al., 2006; Tavares et al., 2019):

- a mixture of combustible gases syngas, CH_2, CH_3, CH_4 is produced with a high calorific purity and value;
- polymetallic nodules and synthetic products with glassy and vitrified structure similar to ceramic products, with very high hardness with a small volume (Ni et al., 2006; Akishev et al., 2012);
- the syngas obtained can be used to obtain raw materials in the field of mechanical and chemical industry (Ni et al., 2006; Akishev et al., 2012), fuels or directly converted into energy;
- the technological installations processes are carried out in short periods of time are compact (Akishev et al., 2012; Gomez et al., 2009; Loo and Koppejan 2010; Matveev and Rosocha, 2010; Ni et al., 2006), the volume of fuel gas obtained is high.

Design and implementation of plasma conversion technology of municipal waste into electricity and heat requires the performance of the following activities such as establishing the technological conditions and the influence of some technological factors specific for the realization of the plasma conversion technology of waste.

Table 1. The main characteristics of plasma incineration and gasification technologies

Incineration uses oxygen	***Plasma gasification in the absence of oxygen***
- energy convers only to heat; - are emitted into the atmosphere polluting gases with variable composition and negative effect on the environment; - residue is ash which is considered a hazardous waste; - residue can be as much as 30% of original solids volume.	- results in gas which can be used to produce energy; - extremely low levels of emissions; - residue is an inert glass like slag; - residue amounts to around 6-15% of original solids volume.

Plasma gasification is a new technology for recycling municipal waste, depending on the composition of the waste, various gases are obtained, used in cogeneration equipment, resulting in thermal and electrical energy, solid residues are used in the metallurgical industry or in road infrastructure as a hard substrate. (Akishev et al., 2012; Ni et al., 2006), with minimal impact on the environment.

The obtained syngas can be used for obtaining raw materials for chemical and mechanical industry, fuels or directly transformed into electric and thermal energy, the technological installations are compact (Akishev et al., 2012; Matveev and Rosocha, 2010), the technological processes take place in short periods of time, the volume of gas obtained is high.

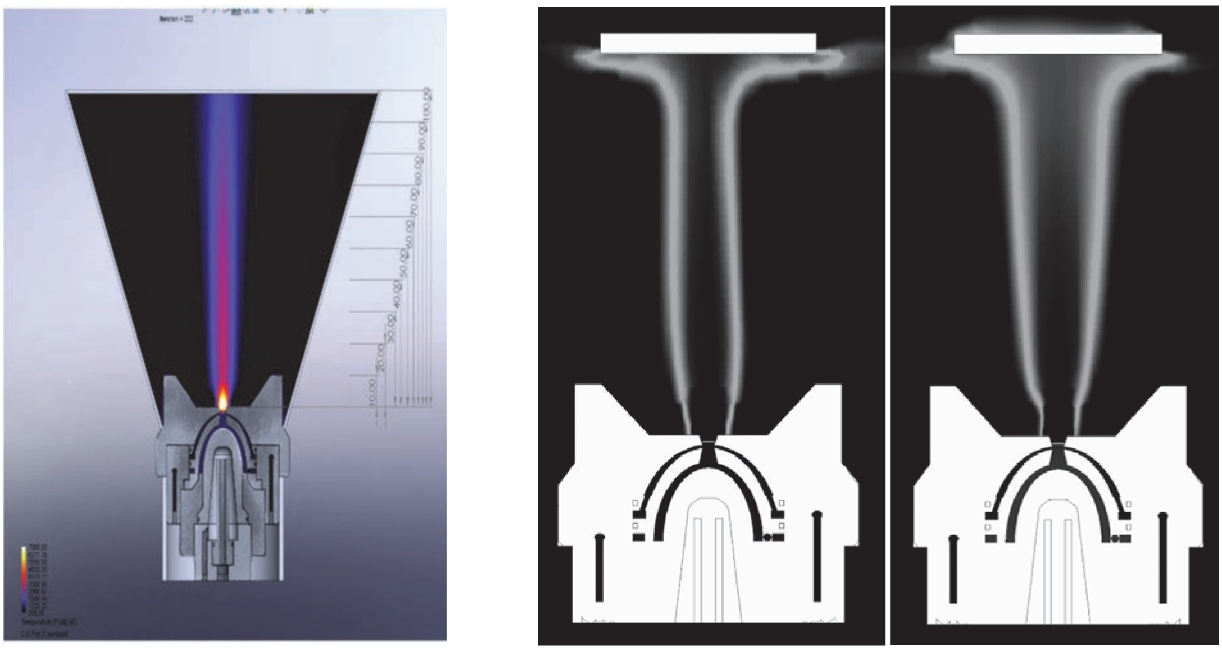
3. Results and discussion

3.1. Hydrogen plasma assisted technology for conversion of municipal waste

The improvement of the plasma technology (Materazzi et al., 2013) that uses the municipal waste as a renewable energy source is done by redesigning and the functional improvement of some equipments within the installation (reactor and hydrogen plasmas, PID predictive thermal conduction processes from the plasma hydrogen reactor enclosure, hydrogen plasma gas purification system).

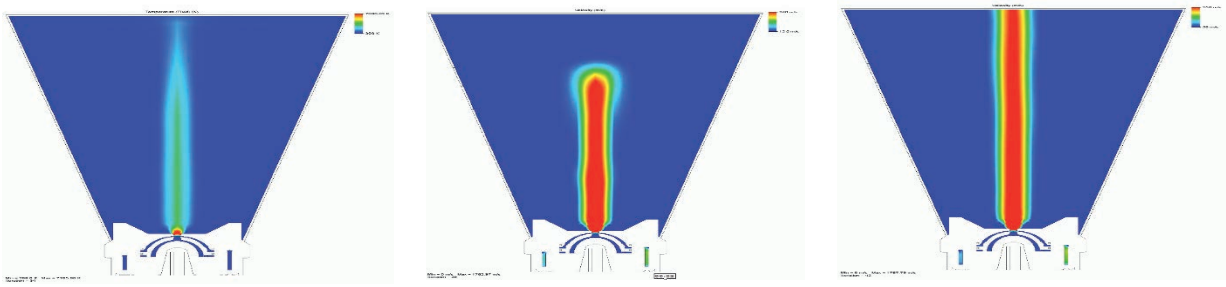
The optimization of syngas production (Akishev et al., 2012; Matveev and Rosocha, 2010) is done by advanced automation of the equipment that controls the power sources that supply the plasma cakes, the control parameters of the control algorithms can be determined by modeling and simulation with the help of Aspen One software or by experimental identification

Mathematical modeling and simulation of the process management system (Li et al., 2020) in plasma plants for waste processing was made with Solidworks, the figures above show the flame shape, hydrogen plasma torch temperature diagram in reactor (the temperature required for waste processing does not exceed 1,000 – 1,600 °C), municipal waste particles displacement in the plasma reactor. The results obtained after modeling the gas flow process and the temperature diagram were used for the design of the hydrogen plasma reactor.



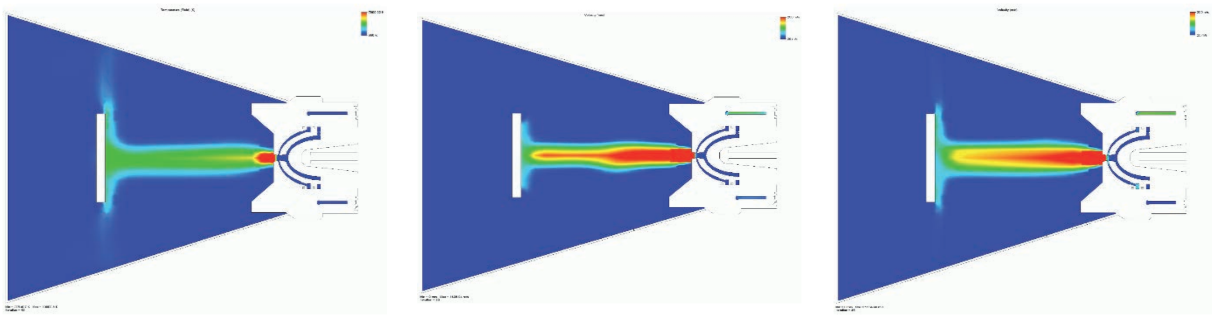
(a) (b)

Fig. 1. Ansys simulation of flame shape, flame length and hydrogen torch temperature diagram (a) flame length and temperature diagram (min 500°C and max 7000°C) ; (b) flame shape



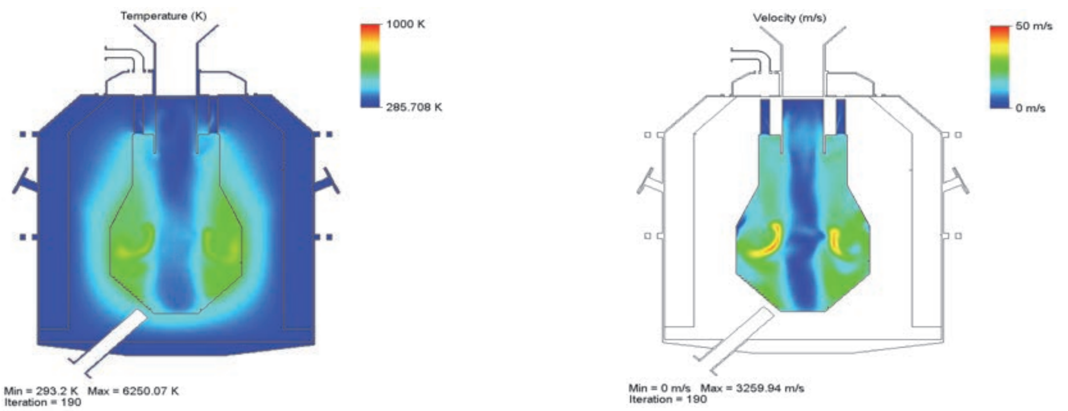
(a) (b) (c)

Fig. 2. Ansys simulation (video) of the hydrogen plasma torch temperature diagram (min 500°C and max 7,000°C): (a) simulation iteration no. 81 (b) simulation iteration no. 147 (c) simulation iteration no. 238

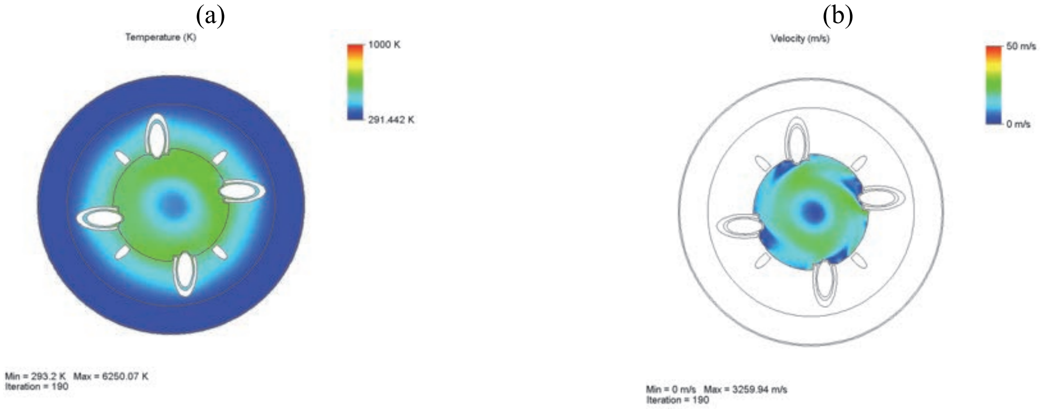


(a) (b) (c)

Fig. 3. Simulation in Ansys (video) of the evolution in time of the velocity displacement of the flame for the hydrogen torch (min 0 m/s and max 1,559.83 m/s):
(a) simulation iteration no. 81 (b) simulation iteration no. 147 (c) simulation iteration no. 238

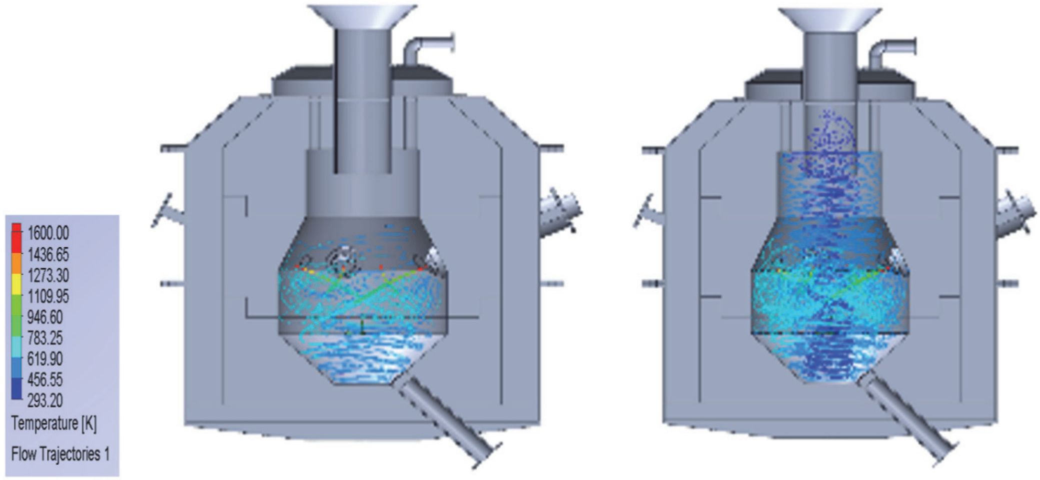


(a) (b)



(c) (d)

Fig. 4. Ansys simulation (video) of the main reactor with plasma on hydrogen (iteration 190):
(a) temperature in variation in the cross section of the reactor; (b) gas velocity variation in the cross section of the reactor
(c) temperature at the plasma level in the reactor; (d) gas velocity at the plasma level in the reactor



(a) (b)

Fig. 5. Solidworks simulation of the temperature of municipal waste particles and their trajectory in the plasma reactor due to the turbulence of the flue gases produced inside: (a) the trajectory of the particles at the beginning of the process (b) the trajectory of the particles at the end of the process

3.2. Equipment for hydrogen plasma conversion of municipal waste

The instalation converts into synthetic gas any solid municipal waste using high temperature plasma technology and hydrogen technology (Matveev and Rosocha, 2010) depending on the purity of the gas obtained, it can be used directly in cogeneration plants for the production of thermal and electrical energy, and if the purity is appropriate through various chemical processes, syngas can be transformed into chemicals with high added value. The heat produced in the process is recovered at various points (Matveev and Rosocha, 2010) in the cooling area of plasma torch, in the heat exchangers between the flue gases and the coolant, in the scrubber area, its conversion into electricity is done with various equipment, the conversion efficiency is variable, the electricity obtained is used locally for power supply some equipment and the surplus is introduced in the national energy system. The following layout describes the overall configuration and main components of the installation designed by authors the prototype installation was realized out within the scientific research of the EFECON project (Fig. 6):

- equipment for processing, crushing and waste disposal of the installation it is a municipal waste preparation equipment for plasma gasification contains a separation and crushing unit, material dosing unit, equipment for supplying the plasma pyrolysis plant;

- the plasma pyrolysis unit is designed for the treatment of municipal waste, the thermal energy produced by the installation is recovered in various points of the installation with the help of properly sized heat exchangers and is used in various equipment of the installation;

- plasma gasification reactor with plasma torch and the hydrogen plasma gas purification system, powered by power sources controlled by automation devices controlled by PID and PID one-step predictive algorithms, accessory modules, the equipment is used for municipal waste processing with a single or multiple plasma torch, it is provided with specialized ports for temperature and pressure transducers and chemical analysis equipment;

- the plasma synthesis gas treatment system aims at the additional treatment of the gases resulting from the waste processing;

- cooling and cleaning system of the slag and the device for collecting and evacuating the solid slag resulting from the gasification by two methods with a liquid and with air the system also contains a heat exchanger for the recovery of thermal energy;

- gas treatment unit resulting in the process composed of the plasma treatment column of the gases resulting from gasification, scrubbing battery for washing and gas separation, filters with a processing capacity correlated with the amount of gas produced per batch, heat exchanger for gasification cooling and their heat recovery, combustible gas collection line, basket and gas exhaust fan;

- module for the treatment of plasma synthesis gases of gases resulting from waste processing;

- cooling, cleaning, conditioning and recovery gas synthesis units, the gas resulting from the plasma synthesis gas treatment system is transferred to the cleaning system to be treated with chlorides, sulfides and other harmful substances using alkaline solutions, to prevent their release into the atmosphere.

The transfer will be made through a heat exchanger, for the recovery of thermal energy and controlled gas cooling. The cleaning system contains a scrubber for washing and separating gases with a processing capacity correlated with the amount of gas produced per batch, the water circulating in this system has the role of removing harmful substances from the gas. The primary washed and separated gases are introduced into a system with filters and vortex separator;

- protective and safety equipment of the plasma pyrolysis plant, exhaust type ventilation systems located in various positions within the installation so as to eliminate all toxic gas leaks and to allow their dispersion as far as possible from populated spaces;

- the central monitoring and control unit of the installation ensures the operation of the waste treatment processes automatically, as well as the monitoring and control of emissions. The system includes a programmable automaton for process control, as well as sensors for monitoring electrical parameters, for temperatures, pressures, water and air flows and sensors for determining CO, H_2, CO_2, O_2, N, NO_x, Cl, S, F etc;

- equipment related to the installation as well: heat and electricity production equipment with cogeneration exhaust gas, air compressor, pump for corrosive liquids.

The Aspen One software (Laaksonen, 2012) for controlling the operation of the plasma system and analyzing the energy efficiency is presented in Fig. 7.

The energy balance and the balance of the raw material and of the products resulting from the processing of the municipal waste with the help of the plasma installation are presented in the Figs. 8-9.

Modeling and simulation of the industrial operation of the hydrogen plasma reactor was realized with the help of the Aspen One software (Laaksonen, 2012; Peters et.al., 2017) the figure below shows the diagram for modeling the process.

These thermo-chemical parameters were compared with the parameters resulting from the modeling and simulation of processes of plasma waste processing resulting a small variation between them.

The projected installation has the following technical features:

- raw material is municipal waste (organic substance) 410 kg/h with humidity 35%, caloric power 13.9 Mj/kg and water as vapor 65 kg/h;

- electricity: 0.200 MWe/h of which: plasma torque = 0.142 MWe/h, water / solid separator = 0.050 MWE/h, organic substance carrier in the reactor = 0.005 MWe/h, measurement and control systems = 0.003 MWe/h.

- slag vitrified 8.2 kg/h, inert material 141.8 kg/h, residual heat of 0.007 Mwt, syngas 325 kg/h which represents 1.533 MWt chemical energy with 10.87 Mj/m^3 calorific value.

4. Conclusions

The paper presents the way in which the operation of hydrogen torch that equip the reactor for municipal waste treatment and the gas purification system was designed and simulated with the help of Ansys and Solidworks software:

- simulation of flame shape, flame length and hydrogen torch temperature diagram, evolution in time of the velocity displacement of the flame for the hydrogen torch (Fig. 1);

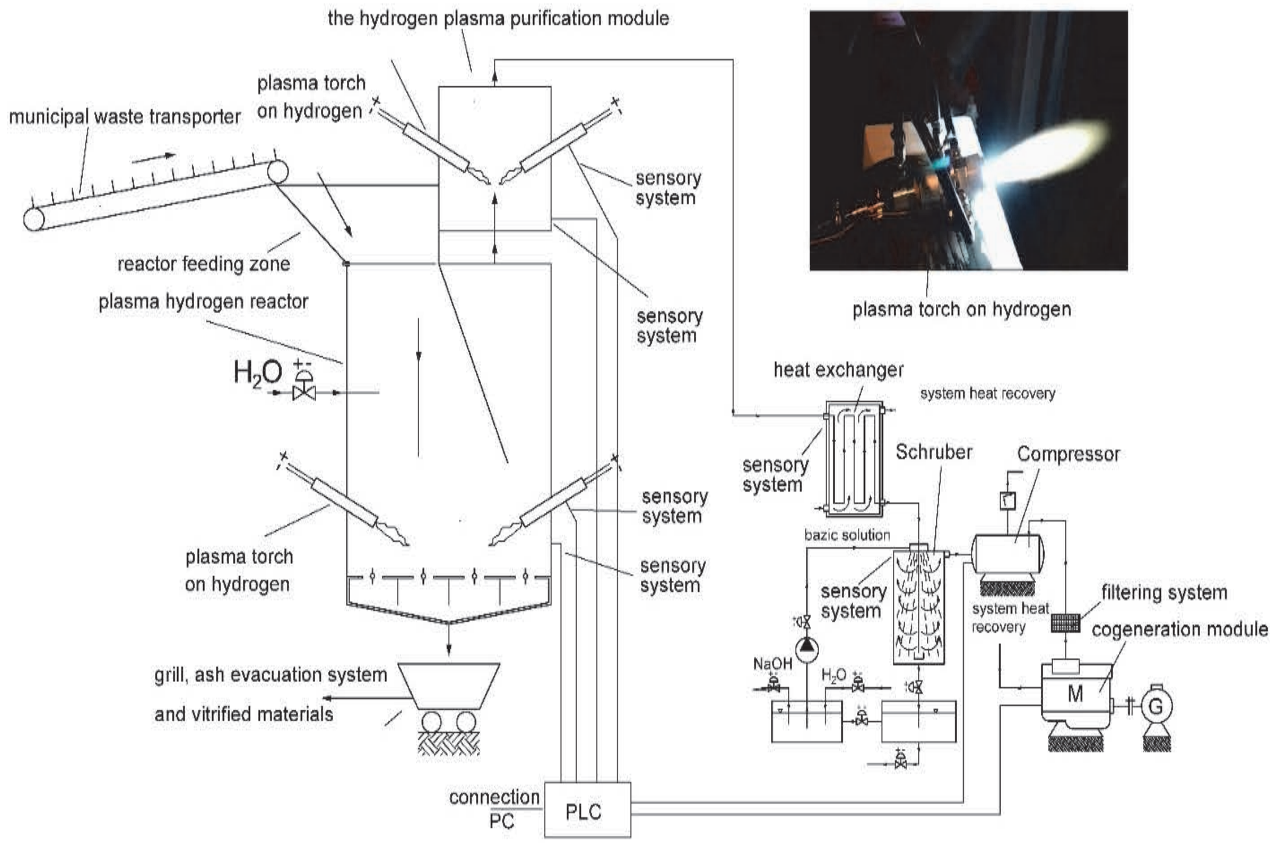


Fig. 6. The schematic diagram of equipment for hydrogen plasma conversion of municipal waste (Lupu et.al., 2020)

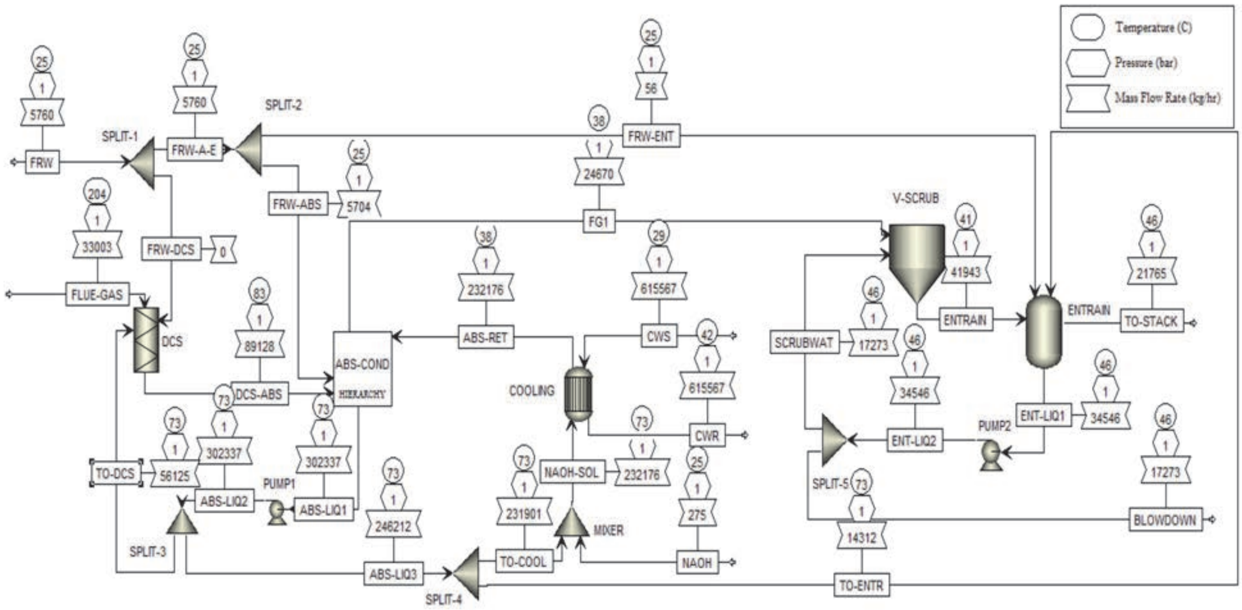


Fig. 7. The use of the Aspen One software for controlling the operation of the plasma system and analyzing the energy efficiency (Laaksonen, 2012)

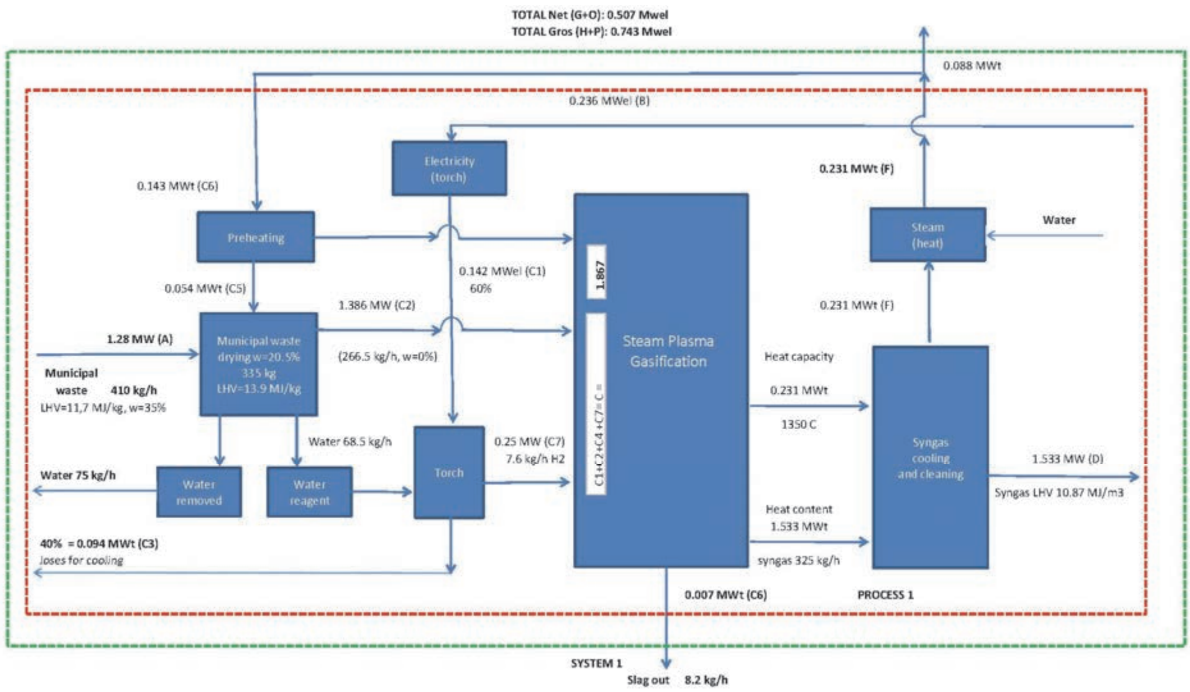


Fig. 8. Functional diagram of the plant (steam plasma gasification reactor) and charts on energy and materials balance

- simulation of the hydrogen plasma torch temperature diagram (Fig. 2);

- simulation in Ansys of the evolution in time of the velocity displacement of the flame for the hydrogen torch (Fig. 3);

- simulation of the main reactor with plasma on hydrogen, temperature and gas velocity in variation in the cross section of the reactor (Fig. 4);

- Solidworks simulation of the temperature of municipal waste particles and their trajectory in the plasma reactor due to the turbulence of the flue gases produced inside.

The schematic diagram of equipment for hydrogen plasma conversion of municipal waste is presented in Fig. 6 and the use of the Aspen One software for controlling the operation of the plasma system and analyzing the energy efficiency (Fig. 7). Figs. 8-9 presented the functional diagram of the plant and charts on energy and materials balance. Following the experimental validation of the results of modeling and simulation of the reactor, plasma torches and of the command and control system, the installation allows the achievement of the following technological parameters:

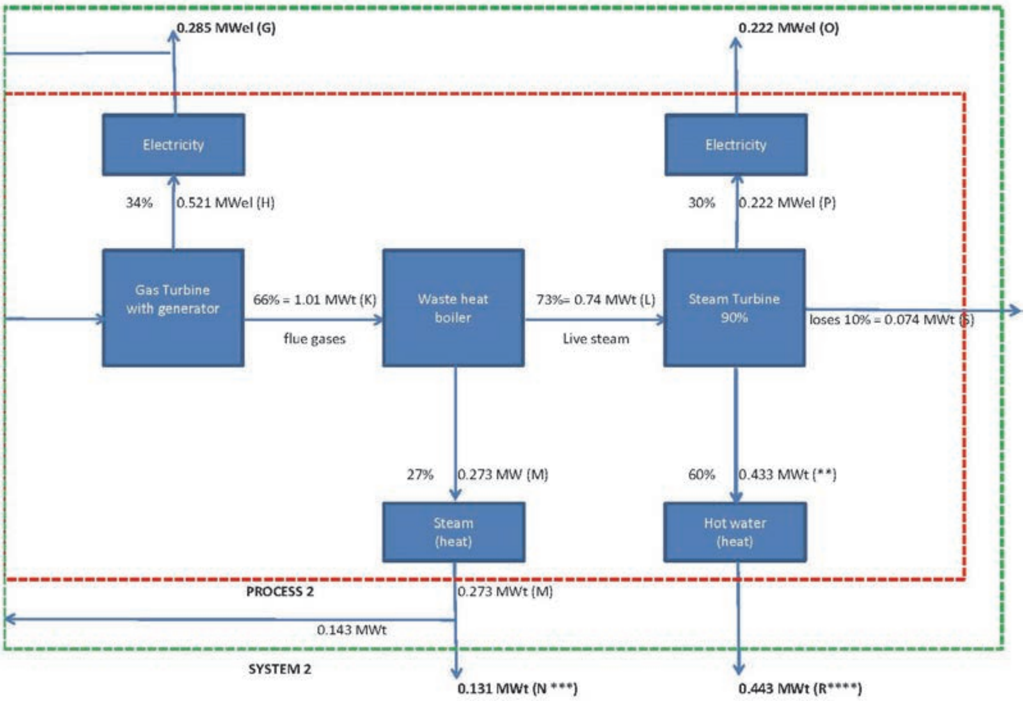


Fig. 9. Functional diagram of the plant (cogeneration system) and charts on energy and materials balance

Table 2. Balance conversion of thermal energy into electricity

System electrical efficiency (gross):	(H+P)/A	58.00%
System electrical efficiency (net):	(G+O)/A	33.20%
System thermal efficiency:	(F+N+R)/A	62.50%
System total efficiency:	(G+O+F+N+R)/A	102.00%
System total efficiency	(H+P+F+N+R)/A	120.00%
Process electrical efficiency (gross):	(H+P)/C	39.8%
Process electrical efficiency (net):	(G+O)/C	27.2%
Process thermal efficiency (gross):	(F+M+R)/C	50.7%
Process thermal efficiency (net):	(F+N+R)/C	42.8%
Process total efficiency:	(H+P+F+M+R)/C	90.5%

- the reduction with about 20-30% of CO_2, and with 30-40% of other greenhouse gases, due to the improvement of the filtration / purification system of toxic gases emitted into the atmosphere;
- reduction of dioxins and furans (carcinogens).
- reduction of quantity of SO_2, SO_3 and NO_x (acid rain factors);

The sludge and sludge produced during the processing of municipal waste containing heavy metals is transformed into chemically inert materials and in terms of environmental impact and disposed of through special devices. The necessary utilities are:

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

The average time of good operation of the component equipment of the plasma installation is approximately 3,000 h in the situation of a continuous operation, the periodic maintenance activity consists in replacing the cakes in the reactor and in the flue gas purification system before the elimination in the atmosphere.

The installation works completely automated, online, from a distance without the intervention of an operator. Economic advantages:

- the installation eliminates the costs related to the planning and management of the municipal landfills, the surface affected by the landfills is returned to the agricultural circuit;
- the analysis of the impact of the plasma installation on the environment shows that it is minimal, the volume of gases emitted into the atmosphere is low and the volume of inert waste is small;
- the cost-benefit ratio is positive following the production of a syngas with a low percentage of hazardous gases or with higher calorific value;
- the use of this installation allows the closure of non-compliant landfills and old pits that due to the urban explosion have reached sites with economic impact and high construction potential;
- the facility destroys medical waste, tires, hazardous waste by treating it with very high temperature plasma.

The operating price of the plant is very low because the plant is equipped with its own cogeneration equipment which produces the electricity required for continuous operation. The price of electricity and heat produced by the installation:

- the use of municipal waste as raw material for energy production leads to reduced production costs;
- reducing the costs of supply, storage and transport of solid/gaseous fuels and import dependency;
- the losses related to the distribution networks are reduced, the electrical/thermal energy produced can be provided to the beneficiaries located near the site of the installation.

Impact on environment:

- elimination of the need for municipal waste dumps;
- efficient recovery of municipal waste by producing renewable energy;
- elimination of the danger of destruction of agricultural land from the landfill infiltration;
- reducing pollutant emissions from classical district heating plants and gradually removing waste dumps.

Acknowledgments

This paper was realized with the support of project EFECON-Eco-innovative products and technologies for energy efficiency in construction, POC/71/1/4-Knowledge Transfer Partnership, Cod MySMIS: 105524, ID: P_40_295, Project co-financed by the European Regional Development Fund.

References

Abbasi T., Abbasi S.A., (2010), Biomass energy and the environmental impacts associated with its production and utilization, *Renewable and Sustainable Energy Reviews*, **14**, 919-937.

AP, (2020), Altair-pyro, On line at: https://altair-pyro.com/faq/

Avram P., Imbrea M.S., Istrate B., Strugaru S.I., Cucos I., Axinte C., Munteanu C., (2014a), Wear Resistance and XRD Analyses of CMoCuNiCrSiBO Coatings Obtained by Thermal Deposition on OLC45 Substrate, *Applied Mechanics and Materials*, **659**, 10-15.

Avram P., Imbrea M.S., Istrate B., Strugaru S.I., Cucos I., Axinte C., Munteanu C., (2014b), Wear resistance and XRD analyses of CNiCrSiBO coatings obtained by thermal deposition on OLC45 Substrate, *Applied Mechanics and Materials*, **659**, 16-21.

Akishev Y., Aponin G., Balakirev A., M Grushin M., Karalnik V., Petryakov A., Trushkin N., (2012), Spatial–temporal development of a plasma sheet in a surface dielectric barrier discharge powered by a step voltage of moderate duration, *Plasma Sources Science and Technology*, **22**, doi: 10.1088/0963-0252/22/1/015004

Begum S., Rasul M., Akbar D., (2014), A numerical investigation of municipal solid waste gasification using aspen plus, *Procedia Engineering*, **90**, 710-717.

Brunner P., Rechberger H., (2015), Waste to energy – key element for sustainable waste management, *Waste Management*, **37**, 3-12.

Cucos I., (2014), Research on the impact of technical, economic and environmental impact of energy management systems for integrated waste, *The Yearbook of the „Gheorghe Zane" Institute of Economic Research*, **23**, 63-72.

Cucos I., Munteanu C., (2015), The experimental researches of advanced systems for managing thermosensitive heat treatments, *Journal of Optoelectronics and Advanced Materials*, **17**, 409-420.

Cucos I., Munteanu C., Mirea C., (2015), The electric furnaces for heat treatment with PID predictiv system, *Applied Mechanics and Materials*, **809-810**, 778-783.

Couto N., Silva V., Monteiro E., Rouboa A., (2015), Assessment of municipal solid wastes gasification in a semi-industrial gasifier using syngas quality indices, *Energy*, **93**, 864-873.

Consonni S., Viganò F., (2012), Waste gasification vs. conventional Waste-To-Energy: A comparative evaluation of two commercial technologies, *Waste Management*, **32**, 653-666.

Farzad S., Mandegari M., Görgens J. (2016), A critical review on biomass gasification, co-gasification, and their environmental assessments, *Biofuel Research Journal*, **3**, 483-495.

Gomez E., Amutha Rani D., Cheeseman C.R., Deegan D., Wise M., Boccaccini A.R., (2009), Thermal plasma technology for the treatment of wastes: a critical review, *Journal of Hazardous Materials*, **161**, 614-626.

Hofbauer H., Materazzi M., (2019), *Waste Gasification Processes for SNG Production*, In: *Substitute Natural Gas from Waste Technical Assessment and Industrial Applications of Biochemical and Thermochemical Processes*, Materazzi M., Foscolo P.H. (Eds.), Academic Press, New York, 105-160.

Judele L., Lepadatu D., Boboc A., Rosu A. R., Cucos I., (2017), *Cold Waste Asphalt Recycling using Fly Ash, Cationic Emulsions and Natural Aggregated Added*, Proceedings of the SGEM2017 Vienna GREEN Conferences, Italy, 43-50.

Laaksonen M., (2012), *Simulation and optimization of an air pollution control system dealing with flue gases from combustion of syngas produced through a municipal solid waste plasma gasification and melting process*, PhD Thesis, Royal Institute of Technology Stockholm.

Li T., Thunman H., Ström H., (2020), A fast-solving particle model for thermochemical conversion of biomass, *Combustion and Flame*, **213**, 117-131.

Lombardi L., Carnevale E., Corti A., (2015), A review of technologies and performances of thermal treatment systems for energy recovery from waste, *Waste Management*, **37**, 26-44.

Lombardi L., Carnevale E., Corti A., (2012), Analysis of energy recovery potential using innovative technologies of waste gasification, *Waste Management*, **32**, 640-652

Lupu M. L., Isopescu D. N., Cucos I., Antonrscu I., Maximeasa S. G., Baciu I. R., (2020), Researches on energy conversion of municipal waste by plasma decomposition for energy-efficiency in civil engineering, *IOP Conf. Series: Materials Science and Engineering,* **789,** IOP Publishing.

Materazzi M., Lettieri P., Mazzei L., Taylor R., Chapman C., (2013), Thermodynamic modelling and evaluation of a two-stage thermal process for waste gasification, *Fuel*, **108**, 356-369.

Materazzi M., Lettieri P., Mazzei L., Taylor R., Chapman C., (2013), Thermodynamic modelling and evaluation of a two-stage thermal process for waste gasification, *Fuel*, **108**, 356-369.

Matveev I.B., Messerle V.E., Ustimenko A.B., (2009), Investigation of plasma-aided bituminous coal gasification plasma science, *IEEE Transactions on Plasma Science*, **37**, 4, 580-585.

Matveev I.B., Messerle V.E., Ustimenko A. B,. (2008), Plasma gasification of coal in different oxidants. plasma science, *IEEE Transactions*, **36**, 2947-2954.

Matveev I., Rosocha L., (2010), Guest editorial classification of plasma systems for plasma-assisted combustion, *IEEE Transactions on Plasma Science*, **38**, 3257 – 3264.

Matveev I., (2016), *Plasma Assisted Combustion, Gasification, and Pollution Control,* Vol. 2, *Combustion and Gasification*, Outskirts Press Publisher, Denver, Colorado, 500.

Martínez J.D., Puy N., Murillo R., García T., Navarro M.V., Mastral A.M., (2013), Waste tyre pyrolysis – A review, *Renewable and Sustainable Energy Reviews*, **23**, 179-213.

Mazzoni L., Almazrouei M., Ghenai C., Janajreh I., (2017), A comparison of energy recovery from MSW through plasma gasification and entrained flow gasification, *Energy Procedia*, **142**, 3480-3485.

Messerle V.E., Ustimenko A.B., (2007), *Solid Fuel Plasma Gasification*. In: *Advanced Combustion and Aerothermal Technologies. NATO Science for Peace and Security Series C: Environmental Security*, Syred N., Khalatov A. (Eds.), Springer, Dordrecht, 141–156.

Messerle V.E., Ustimenko A.B., Lavrichshev O.A., (2016), Comparative study of coal plasma gasification: Simulation and experiment, *Fuel*, **164**, 172-179.

Messerle V.E., Ustimenko A.B., Lavrichshev O.A,. (2017), Plasma coal conversion including mineral mass utilization, *Fuel*, **203**, 877–883.

Messerle V.E., Mosse A.L., Ustimenko A.B., (2018), Processing of biomedical waste in plasma gasifier. *Waste Management*, **79**, 791–799).

Messerle V.E., Ustimenko A.B,. (2019), Plasma processing of uranium-containing solid fuels, *Fuel*, **242**, 447–454.

Miron M., Morariu D. I., Cucos I., Alecu C. I., Judele L., Lepadatu D., (2019), *Photovoltaic Panels Cost Optimization with Flexible Polymer Semiconductor Cells using Fuzzy Logic*, 8th Conference on Material Science and Engineering, IOP Publishing IOP Conf. Series: Materials Science and Engineering, **485**, http://doi.org/10.1088/1757-899X/485/1/012013.

Mukherjee C., Denney J., Mbonimpa E.G., Slagley J., Bhowmik R., (2020), A review on municipal solid waste-to-energy trends in the USA, *Renewable and Sustainable Energy Reviews*, **119**, 124-138

Moustakas, K., Xydis, G., Malamis, S., Haralambous, K.J., and Loizidou, M., (2008), Analysis of results from the operation of a pilot plasma gasification/vitrification unit for optimizing its performance, *Journal of Hazardous Materials*, **151**, 473-480.

Ni M., Leung D., Leung M., Sumathy K., (2006), An overview of hydrogen production from biomass, *Fuel Processing Technology*, **87**, 461-472.

Peters J., Banks S., Bridgwater A., Dufour J., (2017), A kinetic reaction model for biomass pyrolysis processes in Aspen Plus, *Applied Energy*, **188**, 595-603.

Ramos A., Teixeira C.A., Rouboa A., (2018), Assessment study of an advanced gasification strategy at low temperature for syngas generation, *International Journal of Hydrogen Energy*, **43**, 10155-10166.

Youngchul B., Moohyun C., Soon-Mo H., Jaewoo C., (2012), *Thermal Plasma Gasification of Municipal Solid Waste (MSW),* In: *Gasification for Practical Applications*, Yun Y. (Ed.), Interchopen, Rijeka, Croatia, 183-209.

Sogancioglu M., Ahmetli G., Yel E., (2017), A comparative study on waste plastics pyrolysis liquid products quantity and energy recovery potential, *Energy Procedia*, **118**, 221-226.

Surov A.V., Popov S.D., Popov V.E., Subbotina D.I., Serba E.O., Spodobin V.A., Nakonechny Gh.V., Pavlov A.V., (2017), Multi-gas AC plasma torches for gasification of organic substances, *Fuel*, **203**, 1007-1014.

Tavares R., Ramos A., Rouboa A., (2019), A theoretical study on municipal solid waste plasma gasification, *Waste Management*, **90**, 37-45.

Zhang Q., Dor L., Fenigshtein D., Yang W., Blasiak W., (2012), Gasification of municipal solid waste in the plasma gasification melting process, *Applied Energy*, **90**, 106–112.