



PILOT INSTALLATION FOR THERMAL PLASMA TREATMENT OF PLASTIC WASTES

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ABSTRACT

This paper describes the idea of obtaining liquid and gaseous fuels from plastic wastes in a process of plasma gasification/pyrolysis. The paper explains the concept of plasma gasification/pyrolysis of plastics, as well as the working principles of a prototype installation, based on this concept. It also presents results connected with obtained gases. The paper describes general working principle of the installation and a role of its individual elements in the process of gasification. Basic parameters of the installation work, which were appointed during the research are given. Plasma treatment was used for pyrolysis or gasification of polyurethane (PUR). As a result, mostly gaseous products were obtained. The average temperature inside the reactor varied between 900 and 1000°C. Depending on the process, as a plasma agent nitrogen, air or mixtures of both were used. Changes in the amount of air resulted in the gas composition. The best results were obtained with an air excess coefficient (λ) of 0,4 and 0,5.

Keywords: plastic; plasma; pyrolysis; gasification



1 Introduction

Wastes are unavoidable part of human activity. With the growth of population and industrial development the amount of produced wastes is increasing. That causes problems with landfilling. In developed countries the amount of annual production of urban wastes per capita is between 400 and 760 kg while the global production is estimated to be 1,2-1,6 billion tons [16]. In constantly increasing stream of wastes the participation of plastics, which do not putrefy in natural environment, is growing. Because of that plastics are recycled or utilized. The latter method is also applied to toxic and dangerous materials such as medical wastes [22]. The most popular way of utilization is combustion, but because of its production of damaging flue gases great interest is put into pyrolysis and gasification.

Plasma application for thermal treatment of organic materials may contribute to resolving the serious problem of utilizing contaminated wastes, both bacteriologically and chemically – mostly with hydrocarbon compounds. Attention of researchers is lately focused on using thermal plasma in a process of utilization of urban wastes which include hospital and industrial wastes, especially dangerous organic chemical compounds (phenol, chlorinated biphenyls and dioxins – PCBs, PCDDs) [2, 8-10, 18, 19, 22]. Plasma technology finds its application also in a process of combustion and gasification of organic solid materials (biomass and plastics) [8-10, 12, 16, 23, 24].

Pro-ecological policy of highly developed countries, especially members of the European Community, is meant to be some kind of encouragement for development of plasma technology to utilize wastes. Current studies aim to achieve a better efficiency and quality regarding thermal processing of wastes, what will effect on reducing emission of dangerous gases - including greenhouse gases. Results of pilot researches shows, that using a plasma technology to obtaining liquid fuels from biomass and urban wastes may be effective as well as environmentally sound [7, 21]. Also the worldwide increase in prices of petroleum cause interest in processes used for obtaining fuels from gasification of coal and alternative fuels like plastic wastes, biomass, sewage sludge and organic wastes [2, 11, 17, 21]. Significant amounts of hydrogen, the “fuel of the future”, in gas obtained from gasification of biomass is also an important factor [1].

Plasma is roughly defined as a more or less ionized gas. Many researchers considered plasma as a fourth state of matter. Plasma may be generally divided into three types: high temperature plasma which is also called quasi-equilibrium plasma, thermal plasma (also called quasi-equilibrium plasma) and non-thermal plasma (non-equilibrium plasma or cold plasma). Plasma has been used for more than one hundred years, but studies concerning its fundamentals and applications are still being performed [2, 10, 20]. Plasma is a high temperature, strongly ionized medium with lots of radicals. Under such conditions organic substances undergo fast decomposition to gaseous and liquid products (e.g., CO, CO₂, CH₄, C₆H₆, N₂, H₂O). Furthermore, plasma makes a fuel mixture more reactive due to a thermal dissociation of many gaseous products with production of radicals (H, O, N, C, S, CN, OH, NH, CH, CH₃, ...). Additionally, during the process, ionization of decomposed products produce positive ions (C⁺, H⁺, N⁺, CO⁺, O⁺, Si⁺, K⁺ and others) and negative ions (O⁻, H⁻, N⁻ and others), which make gasification/pyrolysis process easier.



As an example, during plasma gasification of hospital wastes, which include cellulose (paper), polyethylene (plastic) and water, gasification reaction may be written in simplistic way as showed below:



According to the research [4] gasification of 1 kg of hospital wastes with following gravimetric composition: 60% of paper, 30% plastic and 10% water, requires 1 kWh of electric energy and at the same time produces syngas, which after conversion to electric energy, gives 3 kWh – this may be a sign of profitability of this venture. Using plasma gasification/pyrolysis technology instead of traditional combustion seems especially justified when utilized waste stream contains significant amounts of organic wastes. Syngas obtained during process, as a potential source of energy, decrease costs of utilization notably [18]. Great amounts of hydrogen in syngas makes plasma gasification of alternative fuels additionally valuable. General idea of plasma gasification/pyrolysis installation, major components and streams are shown at Figure 1.

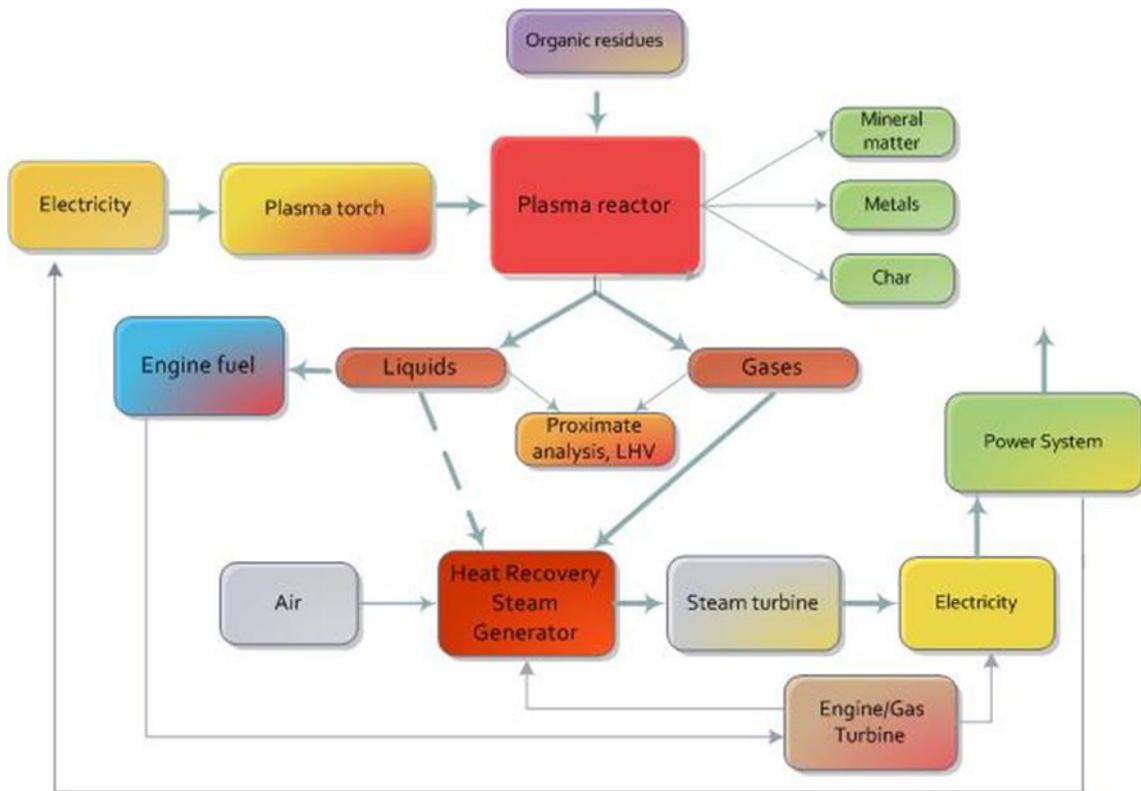


Figure 1. Diagram of organic materials plasma gasification installation.

The most common source of plasma for plasma gasification reactors are so called arc plasma torches. They are based upon a bow discharge in DC or AC electric field, most often in power frequency, obtained between electrodes [2, 9, 10, 18, 19, 21, 23]. Most often, gases used to produce plasma in arc plasma torches are: argon, nitrogen, CO₂, steam or mixtures of them [6, 9, 10, 19, 21, 23]. The allocation of plasma torches, feedstock inlet and product gases outlet is often crucial regarding the general outcome of the process.



2 Experimental

2.1 RESEARCH INSTALLATION

The block of plasma gasification is a main element of the installation. It consists of the gasification reactor and plasma torches which are shown in Figure 2 and Figure 3. Because of the high energy density and high temperature in a plasma canal (which reaches a few thousand K in a space between electrodes and several thousand K in the center of the plasma canal) electrodes in plasma torches are usually cooled by a water and an average time of living for electrodes is between 100 and 500 h in an oxidative atmosphere and to 3000 h if a protective gas is used. The time of living for electrodes depends also on a material they are made of [10]. On a basis of own researches over construction of the plasma torches with cylindrical recess electrodes, which is called recess plasma torch (Figure 3), it is assessed that exploitation time of the plasma torch with electric power about several dozen of kW supplied with air as a plasma agent is about 120 hours and it is declining with a rise of the plasma torch power [5, 13-15].

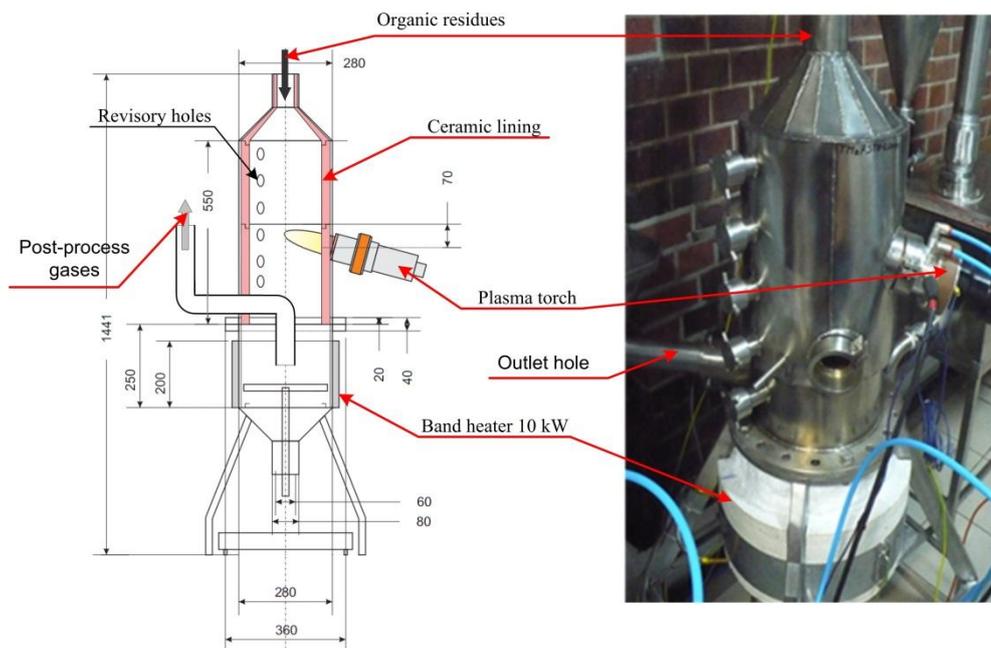


Figure 2. Reactor for plasma gasification of organic wastes.



Figure 3. Plasma torch PW 15 with a nominal power of 15 kW.



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During preliminary tests nitrogen and argon were used as a plasma agents. Using those plasma agents should result in extending lifetime of electrodes.

Preliminary tests showed that during thermal processing of plastics, using arc plasma torches, some problems with feeding system occurred; therefore, feeding system has been modified. In the described reactor feedstock is delivered into the reactor freeboard in powdered form, using self-developed pneumatic feeding system. Treated material is being fed over the plasma flame zone through upper revision hole.

Integral elements of plasma gasification pilot plant are: section of electricity power supply with a microprocessor analyzer of the electric network parameters, specialized electro-energetic power supplies adjusted to supply plasma devices, section supplying plasma torches with a plasma agent equipped with electronic mass flow meters and a system for preparation and feeding, with a control system that allows to monitor the amount of material fed. Figure 4 shows the fundamental elements of the pilot installation for a plasma gasification.



Figure 4. View of the fundamental elements of the plant used in a plasma gasification of wastes.

Additionally, cooling water installation is equipped with rotameters and sensors to control outlet and inlet water temperature of cooled elements.



2.2 ANALITIC METHODS

Post-process gases were being cooled down and collected for analysis with two platemark spouts located on the cooler's outlet. Composition was monitored constantly during the whole experiment and saved in a computer memory. Chemical composition analysis was being performed in a real time, using two different devices. Device called GAS 3000 R detected main constituents of the gas (CO, CO₂, H₂ and CH₄). Dual beam Non Dispersive Infra-Red (NDIR) detector obtained volumetric concentration of CO, CO₂, CH₄. Thermal Conductivity (TCD) detector was used to detect H₂ volumetric concentration [25]. Flame Ionization Detector in a device called Thermo FID was being used to estimate Total Hydrocarbon Content (THC). The device has given, as a result, amount of propane equivalent to the carbon content of all the hydrocarbons burned in the detector. That allowed to estimate the chemical energy bound in all the tar components present in the post-process gases.

2.3 PROCESS

Plasma treatment was used to gasify/pyrolyse granulated polyurethane (PUR). Air or air + nitrogen mixtures were being used as plasma agents. Polyurethane had been comminuted before being fed into the plasma treatment reactor. Particle size did not exceed 500 µm. Gaseous, liquid and solid products were obtained as a result. Composition and Higher Heating Value of feedstock material are given in Table 1. During the startup phase reactor was being heated up until it reached thermal stability and temperature slightly exceeded 500°C. Temperatures obtained during plasma treatment were higher, due to addition of hot plasma gases. Parameters of the plasma treatment process are given in Table 2.

Table 1. Composition and Higher Heating Value of polyurethane.

HHV [MJ/kg]	C ^a [%]	H ^a [%]	N ^a [%]	O ^a [%]
27,3	67,8	6,2	2,3	23,7

Table 2. Parameters of the plasma processing of polyurethane.

Plasma torch gas input		Average temperature in the reactor	Outlet gas temperature	Plasma torch power
Air	N ₂			
[l/min]	[l/min]	[°C]	[°C]	[kW]
0	214,5	713	625	24
60	152,0	827	700	
100	111,3	843	720	
130	85,3	860	776	
160	54,1	887	775	
211,3	0,0	983	845	
251,3	0,0	1070	911	



3 Results

Gaseous products consisted of main components which are typically obtained during every gasification: carbon monoxide, carbon dioxide, hydrogen and insignificant amounts of methane as well as some other hydrocarbon compounds (which may be partly tar compounds). Produced gas was in most of the cases flammable, although its Lower Heating Value was relatively low. Experimental results has given an opportunity to make operational characteristics for the pilot installation.

Lower Heating Value as a function of λ coefficient (Figure 5) is useful in terms of proper system setup. This diagram might prove its value when the need of maximizing of product gas Lower Heating Value becomes dire.

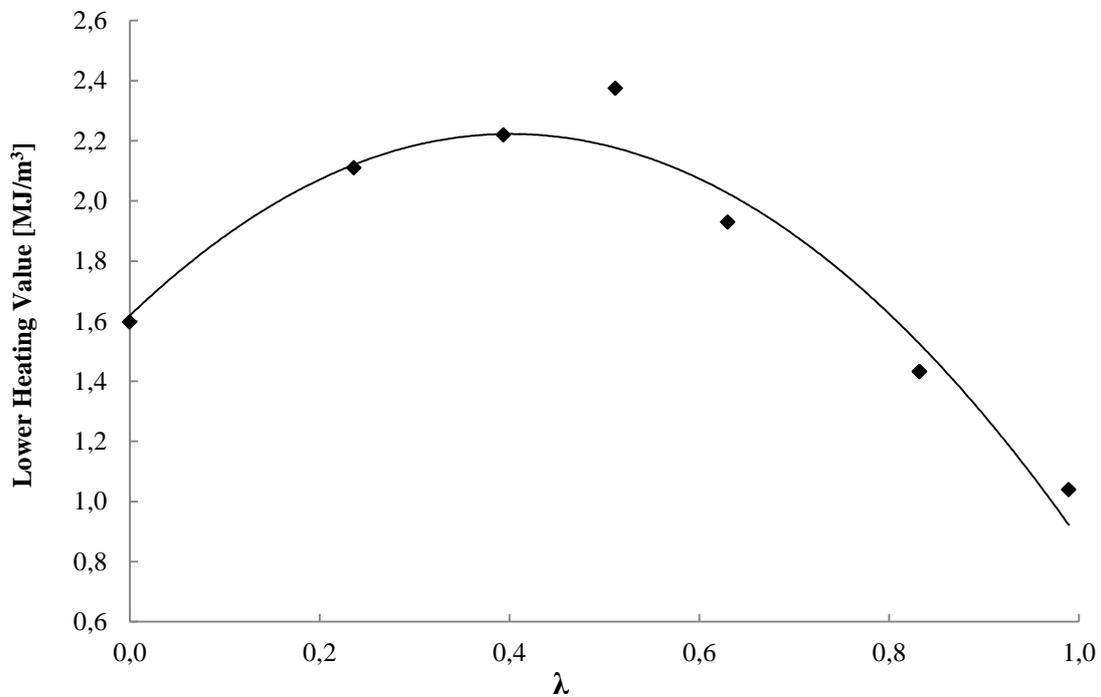


Figure 5. Lower Heating Value of product gas as a function of λ coefficient

After significant number of experiments had been performed, cooler became a subject of an inspection. Deposit inside the cooler consisted of thick, viscous tar compounds and solid particles, but the amounts were insignificant (not enough to perform detailed chemical analysis) comparing to the amounts of raw material (PUR) treated. Flame Ionization Detector analysis results for different levels of λ coefficient are shown at Figure 6.

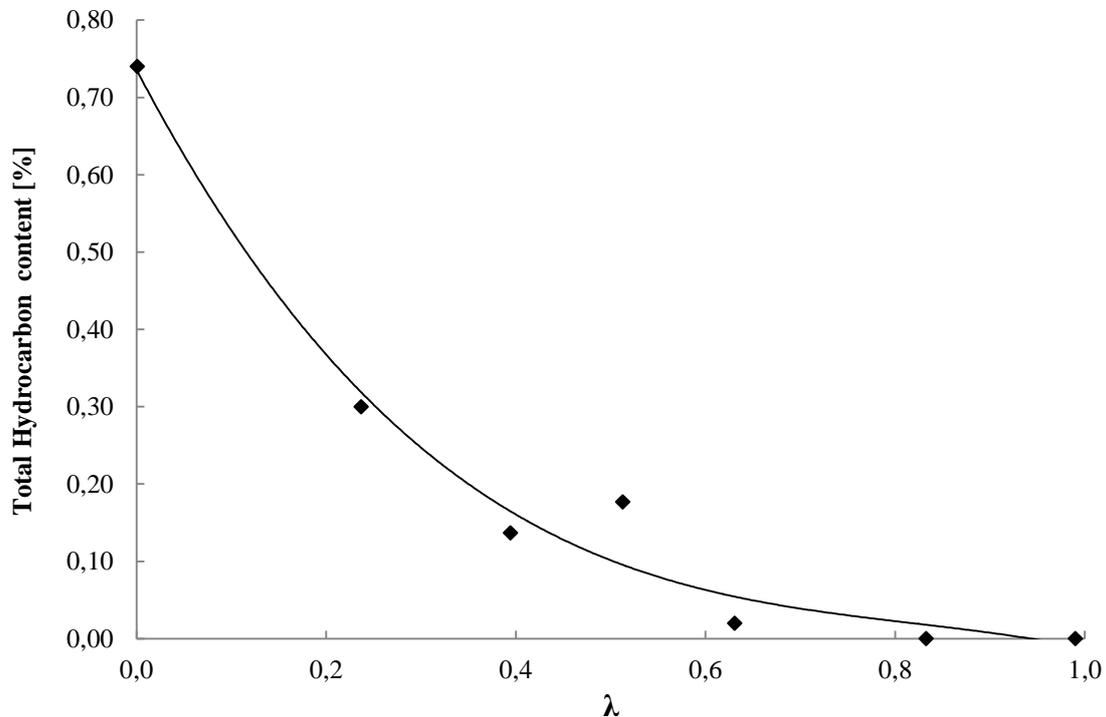


Figure 6. Total Hydrocarbon content as a function of air excess factor (λ) coefficient

Figure 6 might be used as an operational characteristic might be used for rough prediction of light tar level in the gaseous products. That would let the device to be adjusted further, depending on the gas utilization technology and its requirements.

Flame Ionization Detector analysis did not allow to specify hydrocarbon compounds in details, but it seems to be highly probable, that they were limited to light hydrocarbons (e.g. ethane, propane) and light tar compounds (e.g. benzene, toluene), since cool gases were obtained to perform Flame Ionization Detector analysis.

It shall not be overlooked that the maximum for LHV(λ) function is about “half way” between the pyrolysis and the “low tar area” for gasification. Therefore it’s a matter of choice, whether the system user prefers to maximize product gas calorific value, minimize tar content, or set up a reasonable compromise in order to meet the requirement of gas utilization device, at the end of the process line.

Amounts of carbon converted into carbon dioxide and carbon monoxide were estimated as a sort of indicator of thermal treatment performance. Installation is able to achieve reasonably good carbon conversion levels (Figure 7) along the diagram area, starting from λ close to 1,0 up to the point where Lower Heating Value reaches its maximum (Figure 5). That makes sense and might be considered as a sort of confirmation for other results. Maximum for Lower Heating Value is achieved because most of the reactant is converted and decreases soon after because concentration of carbon dioxide in the product gas is starting to grow.

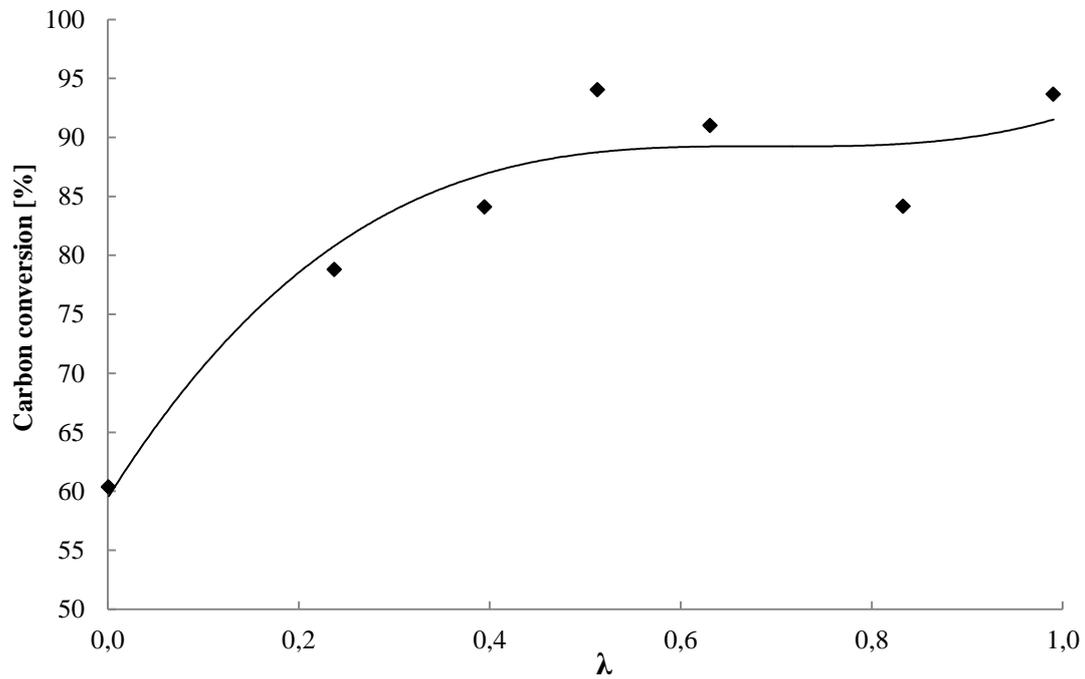


Figure 7. Carbon conversion as a function of λ coefficient

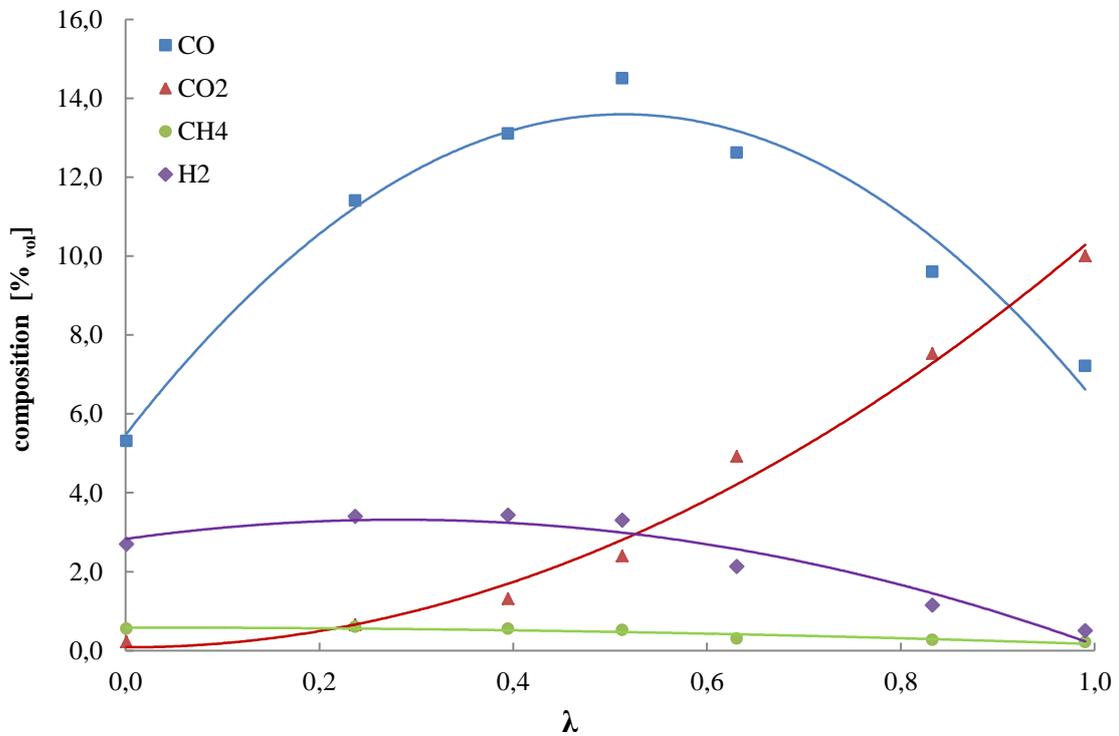


Figure 8. Composition of product gas as a function of λ coefficient



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Figure 8 shows trends of the main gas components formation as a function of λ . It's important to notice, that during the process hydrogen, "the fuel of the future", is produced. Maximum hydrogen concentration is situated (at λ axis) quite close to the maximum Lower Heating Value from Figure 5 (λ around 0,4).

It might be stated as a conclusion, that processing of plastics to obtain gaseous fractions of fuels can be done, using described plasma installation. Polyurethane processing attempts resulted with low-calorific mixture of combustible gases (1,0-2,5 MJ/m³). The highest calorific value was obtained with λ close to 0,5. In that range also small amounts (about 0,2 %) of light hydrocarbons (including light tars) were produced (Figure 6).

Soot particles and heavy tars found in the cooler are suspected to be a result of aromatic structure of PUR. Obtained products have been delivered to an independent laboratory in order to perform more detailed analysis. Unconverted carbon along with particulate matter may be removed from the gas stream using some de-dusting devices but that brings some unwanted side effects. Using scrubbers is related with heat loss due to gas cooling. Filters are quite sensitive for tar content, however results show that it's possible to minimise the amounts of tars in the gas. It comes with a price - some decrease in product gas Lower Heating Value.

Increase in process temperature seems to be the right course for further investigation. It might be achieved by better insulation or adding another plasma torch (one or more) into existing sockets in the reactor.

Results obtained with present plasma installation (reactor construction) and identified possibilities for further improvements make this type of installation still a promising technology for the future.



4 Acknowledgements

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LIST OF SYMBOLS AND ABBREVIATIONS

<i>PUR</i>	polyurethane	[-]
<i>THC</i>	total hydrocarbon content	[%]
<i>HHV</i>	higher heating value	[MJ/kg]
<i>LHV</i>	lower heating value	[MJ/m ³ _n]
λ	excess air coefficient	[-]
PM	particulate matter	[-]

REFERENCES

1. Alex C.C. Chang, Hsin-Fu Chang, Fon-Jou Lin, Kuo-Hsin Lin, Chi-Hung Chen. 2011. Biomass gasification for hydrogen production. *International Journal of Hydrogen Energy* 36. 14252-14260.
2. Bonizzoni, G. Vassallo, E. 2002. Plasma physics and technology; industrial applications. *Vacuum* 64. 327–336.
3. Borkiewicz, J. 2002. Proekologiczne technologie utylizacji odpadów (Pro-ecological technologies for thermal utilisation of waste). *Inżynieria Ekologiczna* nr 6; 159-174.
4. Borysenko, M. Lelyukh, M. Petrov, S. Zhovtyansky, V. Chernets, O. Korzhyk, V. Marynsky, G. Kostash, S. Popov, V. 2009. The plasma technology for the processing of carbon containing raw materials. *Prace Instytutu Nafty i Gazu* nr 162, Wydanie konferencyjne -Efektywność Energetyczna 2009, Instytut Nafty i Gazu, Kraków.
5. Bukowski, P. Kobel, P. Kordylewski, W. Mączka, T. 2010. Use of cavity plasmatron in pulverized coal muffle burner for start-up of a boiler, *Rynek Energii*, nr 1; 132-136.
6. Grigaitiene, V. Snapkauskiene, V. Valatkevicius, P. Tamosiunas, A. Valincius, V. 2011. Water vapor plasma technology for biomass conversion to synthetic gas. *Catalysis Today* 167; 135–140.
7. Heberlein, J. Murphy, A. 2008. Thermal plasma waste treatment, *J. Phys. D: Appl. Phys.* 41, 053001 (20pp).
8. Herdrich, G. Auweter-Kurtz, M. 2006. Inductively heated plasma sources for technical applications. *Vacuum* 80; 1138–1143.
9. Hiroshi Nishikawa, Masaaki Ibe, Manabu Tanaka, Tadashi Takemoto, Masao Ushio. 2006. Effect of DC steam plasma on gasifying carbonized waste. *Vacuum* 80; 1311–1315.
10. Huang, H. Tang, L. 2007. Treatment of organic waste using thermal plasma pyrolysis technology. *Energy Conversion and Management* 48, 1331-1337.



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11. Jones, P. 2009. London's waste to get the plasma treatment. *Modern Power System*, June 2009, Vol. 29 Issue 6, 27-28.
12. Luche, Q. Falcoz, T. Bastien, J. P. Leninger, K. Arabi, O. Aubry, A. Khacef, J. M. Cormier, J. 2012. *Plasma Treatments and Biomass Gasification*. IOP Conf. Series: Materials Science and Engineering 29.
13. Kobel, P. Kordylewski, W. Mączka, T. 2009. Zastosowanie plazmotronu wnekowego do zapłonu mufłowego palnika pyłowego (Recess plasma torch use for muffle burner ignition). *Efektywność energetyczna 2009*, Międzynarodowa Konferencja Naukowo-Techniczna, Kraków, 21-23 września 2009, Kraków: Instytut Nafty i Gazu, 2009. s. 187-190.
14. Kobel, P. Kordylewski, W. Mączka, T. Kordas, R. Milewicz, M. Modrzejewski, K. Zastosowanie plazmotronu wnekowego w mufłowym palniku pyłowym do rozruchu kotła energetycznego: Aktualne problemy budowy i eksploatacji kotłów (Use of recess plasma torch in muffle burner for power plant boiler startup: present problems of boilers construction and exploitation). Jubileuszowa Konferencja Kotłowa 2009 z okazji 60-lecia Fabryki Kotłów RAFAKO SA w Raciborzu, Szczyrk, 13-15 października 2009, Prace Naukowe, Monografie, Konferencje - Politechnika Śląska. Instytut Maszyn i Urządzeń Energetycznych; z. 23, 2009. s. 33-46.
15. Kordylewski, W. Mączka, T. Kordas, R. 2009. Urządzenia rozruchowe plazmotronu dużej mocy (High-power plasma torch startup devices). *Przegląd Elektrotechniczny*. R. 85, nr 10; 116-119.
16. Popov, V. E. Bratsev, A. N. Kuznetsov, V. A. Shtengel, S. V. Ufimtsev, A. A. 2011. Plasma gasification of waste as a method of energy saving. *Journal of Physics: Conference Series* 275.
17. Pravat, K. Swain, L.M. Das, S.N. 2011. Biomass to liquid: A prospective challenge and development in 21 st century. *Renewable and Sustainable Energy Reviews* 15; 4917-4933.
18. Rutberg, G. 2003. Plasma pyrolysis of toxic waste. *Plasma Phys. Control. Fusion* 45; 957-969.
19. Seok-Wan Kima, Hyun-Seo Park, Hyung-Jin Kim. 2003. 100 kW steam plasma process for treatment of PCBs (polychlorinated biphenyls) waste. *Vacuum* 70; 59-66.
20. Tendero, C. Tixier, C. Tristant, P. Desmaison, J. Leprince, P. 2006. Atmospheric pressure plasmas: A review. *Spectrochimica Acta Part B* 61; 2 - 30.
21. Tendler, M. Rutberg, P. Oost, G. Plasma based waste treatment and energy production, *Plasma Phys. Control. Fusion* 47, (2005) A219-A230.
22. Totczyk, G. 2011. Charakterystyka zanieczyszczeń emitowanych przez zakłady termicznej utylizacji odpadów medycznych (Characteristics of impurities emitted by plants thermally utilising medical waste). *Inżynieria Ekologiczna* Nr 25: 211-221.
23. Van Oost, G. Hrabovsky, M. Kopecky, V. Konrad, M. Hlina, M. Kavka, T. 2009. Pyrolysis/gasification of biomass for synthetic fuel production using a hybrid gas-water stabilized plasma torch. *Vacuum* 83; 209-212.
24. Zhao, Z. Huang, H. Wu, C. Li, H. Chen, Y. 2001. Biomass Pyrolysis in an Argon/Hydrogen Plasma Reactor. *Eng. Life Sci.* 1:5; 197-199.
25. Atut. 2012. Dane katalogowe. Atut Spółka z o.o., ul. Ziółkowskiego 26, 20-834 Lublin. Available online: http://www.atut.lublin.pl/plk/gas3000r_biomasa_pl_09v1.pdf, stan na grudzień 2012.