

## PLASMA GASIFICATION OF WASTE PLASTICS

Tadeusz Mączka<sup>1</sup>, Ewa Śliwka<sup>2</sup>, Mateusz Wnukowski<sup>3</sup>

<sup>1</sup> Institute of Heat Engineering and Fluid Mechanics, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland, e-mail: tadeusz.maczka@pwr.wroc.pl

<sup>2</sup> Department of Chemistry and Technology of Fuels, Faculty of Chemistry, Wrocław University of Technology, ul. C.K. Norwida 4/6, 50-373 Wrocław, Poland, e-mail: ewa.sliwka@pwr.wroc.pl

<sup>3</sup> Institute of Heat Engineering and Fluid Mechanics, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland, e-mail: Mateusz.wnukowski@pwr.wroc.pl

Received: 2012.11.18

Accepted: 2012.12.20

Published: 2013.01.15

### Abstract

The article presents the process of obtaining liquid fuels and fuel gas in the process of plasma processing of organic materials, including waste plastics. The concept of plasma pyrolysis of plastics was presented and on its basis a prototype installation was developed. The article describes a general rule of operating the installation and its elements in the process and basic operation parameters determined during its start-up. Initial results of processing plastics and the directions of further investigations are also discussed. The effect of the research is to be the design of effective technology of obtaining fuels from gasification/pyrolysis of organic waste and biomass.

**Keywords:** plasma processing, plastic, fuel fractions.

## INTRODUCTION

Waste is an inseparable part of human activities. With the growth of the number of population and industrial development, the amount of waste increases, therefore, a problem of their storage appears. In developed countries annual production of municipal waste per one inhabitant is from 400 to 760 kg [16], and global production of municipal waste is estimated at 1.2–1.6 billion tons [3]. In the increasing stream of waste, the share of plastics which do not decompose in natural environment increases. This is why plastics are subjected to recycling or utilisation. The latter form is also used in case of toxic and hazardous materials, such as medical wastes [22]. The most common form of utilisation combustion, however, due to the fact that the process generates harmful gases, more and more frequently pyrolysis or gasification is used as alternatives.

The use of plasma for thermal processing of organic materials may contribute to solving a serious problem concerning utilisation of waste

that is bacteriologically or chemically contaminated – especially with hydrocarbons. In the last few years research was conducted on the use of thermal plasma in municipal waste utilisation, including hospital and industrial waste, also those containing harmful organic compounds (phenol, chlorinated biphenyls and dioxins – PCBs, PCDDs) [2, 8-10, 18, 19, 22]. Plasma technology is also used in the process of combustion and gasification solid materials (biomass and plastics) [8-10, 12, 16, 23, 24].

Intensification of research on the use of plasma techniques for utilisation of wastes is in a harmony with ecological policy of developed countries, especially European Union. The research in this area is aimed at improving the effectiveness and quality of thermal processing of waste, therefore, limiting the emission of hazardous pollutants, including greenhouse gases. The results of pilot research show that the use of plasma technologies to produce liquid fuels from biomass and municipal waste may be both effective and safe for the environment [7]. The use of thermal processing

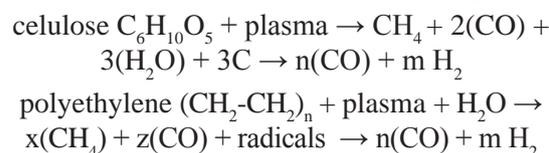
of waste is supported by the aspects of rational and economic energetic management, which result from the increase of produces waste and increasing demand for energy [16, 18]. Worldwide increase of crude oil prices and the shortage of its resources generate interest in alternative systems of obtaining fuels from gasification of coal and alternative sources of energy, such as plastics, biomass, sewage sludge and organic waste [2, 11, 17, 21]. It is also significant that biomass gasification generates significant amounts of hydrogen, which is considered to be the fuel of the future [1].

### PLASMA WASTE PROCESSING

Plasma is defined as ionised, to larger or smaller extend, gas. Many researcher consider plasma to be the fourth state of matter. In plasma technologies, plasma is divided into three types: high temperature plasma(or equilibrium plasma), thermal plasma (or quasi-equilibrium plasma) and non-thermal plasma, non-equilibrium plasma (also cold plasma). The research on the use of plasma started in 19<sup>th</sup> c. but their fastest development took place at the end of previous century. The basic and applied research on plasma, which are going to broaden its use, are still conducted [2, 10, 20].

Thermal plasma is a high temperature, highly ionised medium with numerous radicals. In such conditions chemical substances are quickly decomposed into liquid or gas products, e.g. CO, CO<sub>2</sub>, CH<sub>4</sub>, C<sub>6</sub>H<sub>6</sub>, N<sub>2</sub>, H<sub>2</sub>O. Moreover, under the influence of plasma thermal dissociation of gases takes place with the release of radicals (H, O, N, C, S, CN, OH, NH, CH, CH<sub>3</sub>...),, what increases the reactivity of pyrolysate ingredients. The prod-

ucts of decompositions are ionised into positive (C<sup>+</sup>, H<sup>+</sup>, N<sup>+</sup>, CO<sup>+</sup>, O<sup>+</sup>, Si<sup>+</sup>, K<sup>+</sup> and others) and negative (O<sup>-</sup>, H<sup>-</sup>, N<sup>-</sup> and other) ions, what facilitates the course of gasification/pyrolysis [9]. For example the process of plasma gasification of hospital waste with cellulose (paper), polyethylene (plastic) and water can be illustrated in a simplified reaction of gasification, according to the pattern:



According to the research presented in [4], in order to gasify 1 kg of hospital waste consisting 60% of paper, 30% of plastic and 10% water it is necessary to use c.a. 1 kWh electric energy, and the synthesised gases containing CO and H<sub>2</sub> can be converted into electric energy in the amount of over 3 kWh – this is the premise to prove economic efficiency of the technology. The use of plasma techniques instead of traditional combustion seems particularly justified in case of utilisation of waste with significant share of organic matter. The generated synthesised gas, as a potential source of energy, lowers the costs of utilisation [18]. High amounts of hydrogen in the synthesised gas is an additional argument for the attractiveness of plasma gasification of alternative fuels.

The installation for plasma processing of plastic wastes and eventually contaminated biomass into liquid fuels is based on instant pyrolysis. It consists of the following functional elements: solid fuel preparation for plasma reactor (grinding, melting), thermal processing (plasma processing), ultrafast cooling, synthesised fuel purification (eventually), measurement systems, fuel container (Fig. 1).

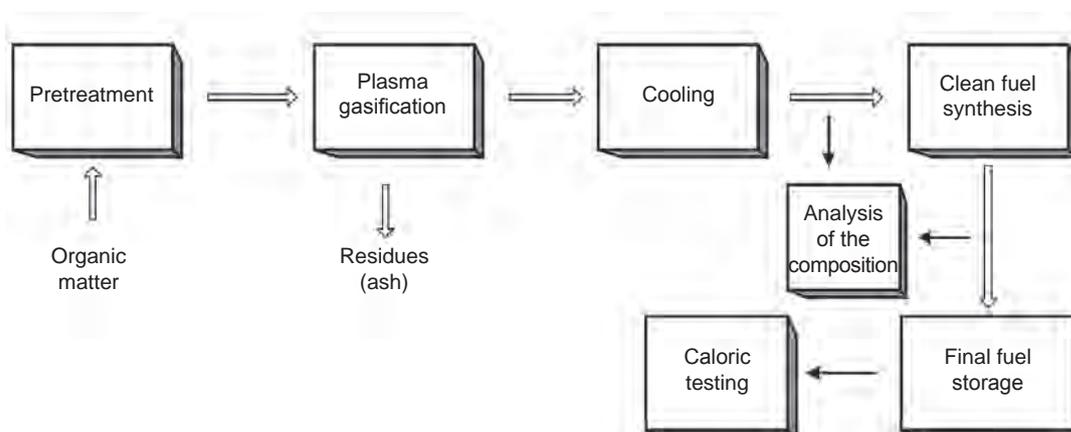


Fig. 1. A scheme of installation for plasma gasification of organic waste

In plasma reactors used for biomass and organic waste gasification, a common source of plasma is the so called arc plasmotrons, based on arc discharge in direct electric field DC or alternating current AC, most often at network frequency, generated between electrodes [2, 9, 10, 18, 19, 21, 23]. In arc plasmotrons plasma generating agents are such gases as argon, nitrogen, CO<sub>2</sub>, water steam or their mixes [6, 9, 10, 19, 21, 23]. Other significant factors include also the method of placing plasmotrons, place of material feeding and the place of gas collection [16].

### EXPERIMENTAL INSTALATION

The most fundamental element of experimental installation is the block of plasma gasification. It is made of a combustion chamber with a specially designed recess plasmotrons (Fig. 2 and 3).

Due to high temperatures and energy densities in the plasma canal (in the region of electrodes that temperatures usually reach a few thousand K, and in the core of plasma canal – a few dozen

thousand K) the electrodes in plasmotrons are cooled with water and average lifespan of electrodes ranges from 100 to 500 hrs in oxidizing environment and up to 3000 hrs in the atmosphere of protective gas. Electrode lifespan also depends on the material of electrodes [10]. On the basis of own research on the construction of plasmotrons with cylindrical (recess) electrodes (Fig. 3) it is estimated that the time of exploitation at a few dozen kW for a plasmotron fuelled with air as a plasma generating agent, is c.a. 120 hrs, and decreases with the increase of plasmotrons power [5, 13].

In the works on plasma processing of organic materials to obtain liquid fuels, nitrogen and argon were used as a plasma generating agent. The framework of research also assumed the use of water steam as a plasma generating gasification agent. The use of enumerated plasma generating agents should result in extension of plasmotrons lifespan.

Previous attempts to use arc plasmotrons for thermal processing of plastics showed certain technical difficulties at the stage of implementing the material into the area of plasma canal. In

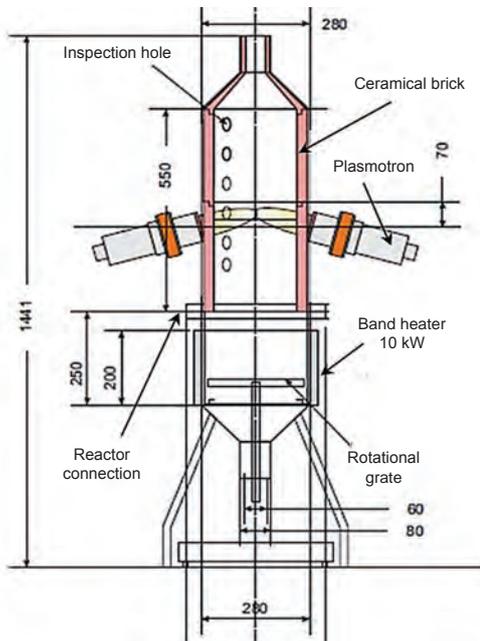


Fig. 2. Reactor for plasma gasification of organic waste



Fig. 3. Cylindrical plasmotrons used in experiments

authors' own research the material was fed pneumatically (in a grounded form) over the plasma flame through the upper opening. The material that left the plasma canal to early was retaken to the plasma by melting and convectional evaporation. This was done with an electric heater with the power of 10 kW, located at the lower part of the reactor (see, Fig. 2).

Other elements of pilot installation for plasma processing were: power section with microprocessor multifunction analyser, specialised power packs adapted to power plasma equipment, plasmatrons fuel section, with electronic mass flow meter, a system of processing and feeding material of gasification with a desktop for monitoring the amount of material feed (Fig. 4).



Fig. 4. Elements of installation for plasma processing of waste

The installation was equipped with water rotameters and sensors to control the temperature of incoming and outgoing water for cooling systems.

## RESEARCH METHODOLOGY

In order to analyse the composition of process gases ( $H_2$ ,  $CH_4$ ,  $CO$ ,  $CO_2$ ) in a real time, gas analyser GAS 3000R was used [25]. On the basis of the composition, the analyser determined the calorific value of the obtained gas. Following its cooling, such a process gas was taken to analysis with a probe placed in a outlet canal of the cooler and was

put into the GAS 3000R analyser. The composition of the process gas was monitored in a constant way throughout the process of plasma pyrolysis and the results were recorded in computer memory.

The identification of liquid products was made in GC 5890 gas chromatograph, coupled with mass spectrometer MS 5971. In order to identify the distribution of protons in aliphatic, olefin and aromatic groups the spectrum of  $^1H$  NMR ( $^1H$  NMR– proton nuclear magnetic resonance spectroscopy) were recorded. The analysis was made on BRUKER AVANCE 300 spectrometer at the frequency of 300.13 MHz. Density, ash content, acidity and moisture content was done according to standards [26–29]. Group composition (the content of hydrocarbons and polar compounds) was determined by a method of liquid chromatography in a silica gel column.

## RESEARCH RESULTS

In the first experiment of plastics pyrolytic processing (eventually with plastics waste as a target material to be processed) the material to be pyrolysed was polyethylene (PE) with the grains smaller than 500 mm. Liquid and gas fractions were obtained (fuel fractions). As a plasma generating agent nitrogen was used. Before the proper pyrolysis, the reactor was heated up until the temperature of outlet gases stabilised at 550 °C. It was only then that the proper process started. The parameters of the process are presented in Table 1.

The composition of the obtained process gas during normal work of the reactor (in stabilised state) was presented in Table 2. During the process, large amounts of hydrogen (also called the fuel of the future) were generated.

Liquid products of plasma processing of polyethylene were condensed and stored in the cooler. Then, samples were taken through release openings at the bottom of the cooler in order to analyse the composition. The products cooled to the temperature of c.a. 20 °C had a consistency similar to grease/Vaseline and a colour similar to cream.

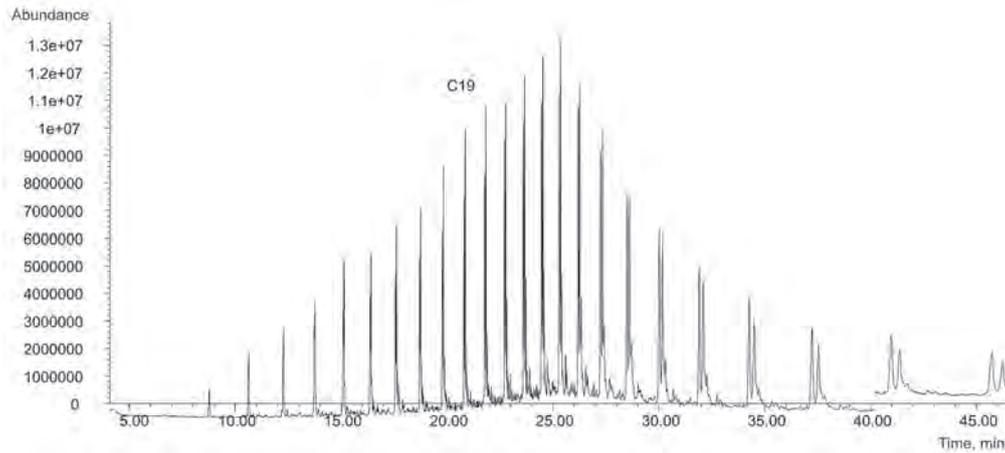
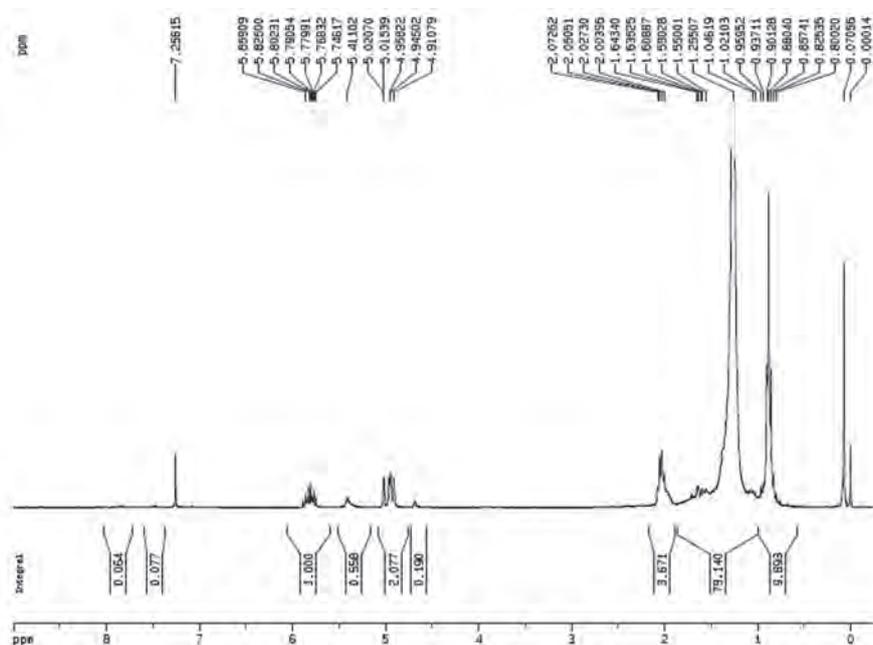
GC-MS analysis showed that the liquid products of plasma pyrolysis of polyethylene are a mixture of aliphatic hydrocarbon homologues with n-alkanes, n-alk-1-enes and alkadienes among them with the number of carbon atoms from C10 (decane) do C33 (trtriacontane) (Fig. 5). In a chromatogram the peaks are registered according to the increasing number of carbon atoms in a molecule, yet for similar retention time the elu-

**Table 1.** The parameters of plasma process of polyethylene (PE) pyrolysis

Material stream (PE) [kg/h]	Plasmotron power [kW]	Stream of plasma generating agent [Nm <sup>3</sup> ]	Temperature above plasmotron [°C]	Average temperature in reactor [°C]	Temperature of gases above reactor [°C]	Temperature of gases after cooling [°C]
3,0	13,5	9,0	1200	750	530	20

**Table 2.** Parameters of process gas obtained during plasma pyrolysis of PE

Hydrogen H <sub>2</sub> [%]	Methane – CH <sub>4</sub> [%]	Carbon oxide – CO [%]	Carbon dioxide – CO <sub>2</sub> [%]	Calorific value kJ/Nm <sup>3</sup>
1,1	2,0	0,3	< 0,01	848,5

**Fig. 5.** Chromatogram of liquid fraction obtained from plasma pyrolysis of polyethylene (PE)**Fig. 6.** <sup>1</sup>H NMR spectrum for liquid product of PE plasma pyrolysis

tion was in the order: n-alkane, n-alk-1-ene and alkadiene with the same number of carbon atoms. The content of the above groups of hydrocarbons was decreasing. The largest share in the obtained liquid was recorded for hydrocarbons from C<sub>18</sub> to C<sub>26</sub> (their peaks were the highest).

Figure 6 presents <sup>1</sup>H NMR spectrum of the pyrolysis of PE. The interpretation of this spectrum proved the results of chemical composition analysis. It was found that the main elements of the examined product are aliphatic groups (-CH<sub>3</sub>, -CH<sub>2</sub>, -CH) and olefin groups, which are giving signals

**Table 3.** Selected properties of liquid fraction of plasma pyrolysis characteristic for diesel fuel and biodiesel

Material	Density [g/cm <sup>3</sup> ]	Volatile compounds + water content [% m/m]	Ash, [% m/m]	Group composition [% m/m]		Acid number [mg KOH/g sample]
				hydrocarbons	polar compounds	
Post-pyrolytic fraction of PE	0,868	6,70	0,290	89,9	4,4	1,52
Diesel fuel	0,800–0,845	–	0,01	–	–	0,2 (for biodiesel*)

\* Diesel fuel consisting 20% of methyl esters of fatty acids from rape oil.

in the range of 0.5–2.0 ppm and 4.5–6.0 ppm accounting for 95.87% and 3.99% respectively. In the range 7–9 ppm, characteristic for protons in aromatic rings, only trace presence of these groups was recorded (0.15%), and in the range 2.0–4.0 ppm (characteristic for protons grouped in  $\alpha$ -CH<sub>2</sub> in aromatic rings) no signals were observed, what implies practically non-aromatic chemical character of the obtained product.

Table 3 presents selected properties of liquid fraction obtained from plasma pyrolysis of polyethylene (PE) determined according to standards [26–29] and, for comparison, selected characteristics of motor fuels (diesel fuel and biodiesel).

In comparison to diesel fuel, the obtained product of PE pyrolysis contains more higher molecular weight hydrocarbons (range of the number of carbon atoms for diesel fuel is C10–C25 and for pyrolysed PE C10–C33), much more aliphatic hydrocarbons especially n-alkanes, which are the ingredients of diesel fuel, responsible for its cetane number. Considering other physical and chemical properties it can be stated that the obtained product has similar properties to diesel fuel. However, the obtained liquid fraction does not seem to be a good basis for motor fuels, due to its solid consistence at room temperature and the presence of unsaturated hydrocarbons, which have negative impact on fuel stability. On the other hand, the product can be a component for heating oil, and after hydrogen improvement, it can be used to produce paraffin.

## CONCLUSIONS

It was shown that in the presented prototype installation plasma processing of plastics in order to obtain liquid fractions of fuels can be done. During the attempts to process polyethylene (PE) low-caloric mixture of combustible gases (c.a. 0,85 MJ/Nm<sup>3</sup>) and a liquid fraction of similar consistence to diesel fuel and grease/vaseline were obtained.

The obtained gas contained traces of CO<sub>2</sub>, and in the products there were traces of aromatic components and acid character. Therefore, the method is more environmentally friendly than traditional utilisation of plastics by combustion. Similar chemical character of the liquid product components, containing almost only homologues of aliphatic carbohydrates and lack of contaminants should facilitate possible further processing and finding their use (e.g. in chemical synthesis or petrochemical industry).

In order to develop an effective method of plasma technology for plastic waste processing, the following works are anticipated:

- proper selection of conditions and parameters of plasma processing,
- selection and characteristics of the input material for research,
- analysis of obtained liquid fuels and residues after plasma pyrolysis,
- modernisation and optimisation of the installation.

The completion of the above actions should result in developing an industrial scale technology.

## Acknowledgments

The installation was built within the development project Application of the plasma technique to biomass and waste gasification for fluid fuel production (Technologia plazmowego zgazowania biomasy i odpadów dla wytwarzania paliw płynnych) funded by the National Centre for Research and Development (contract No. NR06 -0003-10/2010).

## 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. *Inżynieria Ekologiczna*, 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. Wydział konferencyjne – Efektywność Energetyczna, *Prace Instytutu Nafty i Gazu* nr 162, 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.
11. Jones P. 2009. London's waste to get the plasma treatment. *Modern Power System*, 29(6): 27-28.
12. Luche, Falcoz Q., Bastien T., Leninger J.P., Arabi K., Aubry O., Khacef A., Cormier J.M., Lédé 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. Międzynarodowa Konferencja Naukowo-Techniczna "Efektywność energetyczna" 21-23 września 2009, Instytut Nafty i Gazu, Kraków: 187-190.
14. Kobel P., Kordylewski W., Mączka T., Kordas R., Milewicz M., Modrzejewski. 2009. Zastosowanie plazmotronu wnekowego w muflonowym palniku pyłowym do rozruchu kotła energetycznego. Aktualne problemy budowy i eksploatacji kotłów. Jubileuszowa Konferencja Kotłowa 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: 33-46.
15. Kordylewski W., Mączka T., Kordas R. 2009: Urządzenia rozruchowe plazmotronu dużej mocy. *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, Das L.M., Naik 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 Parkb, Hyung-Jin Kim. 2003. 100 kW steam plasma process for treatment of PCBs (polychlorinated biphenyls) waste. *Vacuum*, 70: 59-66.
20. Tendero C., Tixier Chr., 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. 2005. Plasma based waste treatment and energy production. *Plasma Phys. Control. Fusion*, 47: A219-A230.
22. Totczyk G. 2011, Charakterystyka zanieczyszczeń emitowanych przez zakłady termicznej utylizacji odpadów medycznych. *Inżynieria Ekologiczna*, 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. Dane katalogowe. 2012. Atut Spółka z o.o., ul. Ziółkowskiego 26, 20-834 Lublin, [http://www.atut.lublin.pl/plk/gas3000r\\_biomasa\\_pl\\_09v1.pdf](http://www.atut.lublin.pl/plk/gas3000r_biomasa_pl_09v1.pdf), stan na grudzień 2012.
26. PN-90/C-04004: 1990. Ropa naftowa i przetwory naftowe – Oznaczanie gęstości
27. PN-EN ISO 6245: 2008. Przetwory naftowe. Oznaczanie pozostałości po spoieleniu.
28. PN-EN 14104: 2004. Produkty przetwarzania olejów i tłuszczów – Estry metylowe kwasów tłuszczowych (FAME) – Oznaczanie liczby kwasowej.
29. PN-80/G-04511. Oznaczanie zawartości wilgoci.