Plasma gasification of organic containing substances as a promising way of development of alternative renewable power engineering

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Abstract. The paper deals with perspectives of large-scale implementation of the plasma gasification process of solid organic-containing substances as a source of renewable energy. First of all, such substances as wood waste, agriculture waste, solid household waste are considered. Thanks to the process of the plasma high-temperature gasification the energy of their combustion can be completely converted into the energy of the synthesis gas combustion, which use as a fuel for the combined cycle allows electricity generation with efficiency of ~60%.

1. Introduction

World consumption of primary energy in 2011 has made more than 12.274 billion tons in an oil equivalent [1]. This magnitude steadily grows with increase in rates of growth. So from 1990 to 2000 the consumption growth is ~16 %, and in the next decade ~28 %. First of all, it is connected with the economic growth and improvement in living standards of the population. Oil, gas and coal constitute ~87 %, and renewed sources make up hardly more than 1 %. The oil and gas will last for ~50 years, and coal for ~100 years at such rates of consumption of the proven reserves. The back of this process is escalating streams of gaseous, liquid and solid wastes mainly remaining in the environment causing ecological problems and global warming. So, for example, throughout last decades the concentration of the carbon dioxide steadily grows in the atmosphere, and in 2010 the global volume of carbon dioxide emissions has grown on ~5.9 % and for the first time has exceeded 9·10^15 g in a year [2].

Volumes of solid household waste also increase. It is quite apparent that energy needs will only increase, therefore the replacement of fossil fuel by alternative energy sources and use energy in more efficient ways in general is a pressing issue.

Plasma gasification as an alternative energy

Usage of biomass and waste energy is one of the solutions of the problems mentioned above. Biomass has a lower heating value than fossil fuels, nevertheless, it can be also used for production of electric and thermal energy. Besides volumes of biomass annual formation are great enough to cover an essential share of mankind needs in energy already now, and under forecasts [3] in 2050 the global...
potential of biomass energy will be 1135-1300 EJ (without use of algae as biomass) while world consumption on the average, under different scenarios, will reach the order of 826 EJ. One more essential advantage of the biomass usage for energy generation is the absence of the additional emission of carbon in biosphere as the biomass consumes this carbon from biosphere for its formation.

Table 1 tabulates the major types of biomass and wastes and some of their properties.

Table 1. **The major types of biomass and wastes and their properties.**

| Parameter | Feedstock | Units of measurement | Wood waste | Switchgrass | Cow manure | Chicken manure | Sludge | RDF | Peat | Used car tires | Plastic waste |
|-----------|-----------|---------------------|------------|-------------|------------|----------------|--------|-----|-----|---------------|---------------|
| Name      |           |                     |            |             |            |                |        |     |     |               |               |
| Volume    | g/kg      |                     | 50.25      | 49.16       | 50.39      | 53.96          | 48.60  | 49.96| 57.56| 86.13          | 82.91          |
| C         | % mass    |                     | 6.09       | 6.36        | 5.77       | 5.60           | 6.57   | 6.69| 6.10| 6.93           | 12.29          |
| H         | % mass    |                     | 0.20       | 0.63        | 3.94       | 7.92           | 5.15   | 0.96| 2.17| 0.57           | 0.71           |
| N         | % mass    |                     | 0.10       | 0.13        | 1.31       | 0.96           | 1.71   | 0.11| 0.24| 1.73           | 0.14           |
| S         | % mass    |                     | 43.35      | 43.73       | 38.58      | 31.56          | 37.97  | 42.28| 33.88| 3.47           | 2.54           |
| O         | % mass    |                     | 0.00       | 0.00        | 0.00       | 0.00           | 0.00   | 0.00| 0.04| 1.16           | 1.41           |
| Feedstock moisture | % mass | 20.00 | 6.29 | 36.60 | 20.20 | 6.10 | 7.83 | 9.40 | 1.14 | 1.00 |
| Ash content of feedstock | % mass | 0.80 | 8.51 | 25.20 | 21.23 | 36.06 | 8.71 | 16.87 | 13.35 | 28.20 |
| Fuel LHV published | MJ/kg | 13.90 | 15.82 | 6.49 | 12.09 | 12.92 | 15.01 | 16.46 | 33.57 | 28.68 |
| Fuel LHV calculated | MJ/kg | 14.26 | 15.45 | 5.8 | 10.84 | 10.15 | 15.73 | 15.77 | 31.11 | 28.89 |
| Adiabatic temperature of combustion in dry air | K | 2123 | 2304 | 1815 | 2210 | 2562 | 2174 | 2337 | 2621 | 2421 |
| Oxygen consumption needed for complete gasification | g/kg | 9.2 | 129.5 | 0 | 56.8 | 100.7 | 133.0 | 232.0 | 941.2 | 755.0 |
| Oxygen consumption needed for complete combustion | g/kg | 1101 | 1174 | 546 | 923 | 841 | 1202 | 1240 | 2416 | 2235 |
| Maximal yield of chemical energy at complete gasification | MJ/kg | 17.84 | 17.20 | 8.51 | 14.05 | 11.93 | 17.56 | 16.64 | 24.47 | 24.36 |

Wood versus the fossil fuels, mainly does not contain sulphur and other ecologically harmful elements, however its use in a wood-working industry on the economic efficiency considerably surpasses energy use. Therefore, it is expedient to process the remains formed during timber cutting and the municipal waste mainly consisting of wood materials.

Energy crops are called plants, raised for energy applications. They are the major kind of biofuels. Generally, they represent grassy or wood fast-growing plants, for example switchgrass [13] and willow [14]. Algae is another one promising kind of biofuels. Algae do not require fertile lands for their cultivation and they grow practically in any water [15].

Waste of cattle and poultry raising (manure) also are biomass and, accordingly, can be used as the renewed energy source. Their mishandling leads to the bacteriological infection of ground waters [16]. The manure composition, even produced by the same group of animals can vary greatly depending on technologies used for its disposal.

Sewage sludge represents a solid-state component of sewage separated by mechanical methods and
sedimentation at sewage purification plants. Depending on sources of formation they can contain a considerable quantity of mineral inclusions and possess high moisture. Thus a mineral component, as a rule, is difficult to separate from deposits. The moisture containing in pores of sludge particles, can be separated by traditional methods (dewatering, evaporation, and other drying procedures) [17]. Sewage treatment also includes stages of sanitation and recovery of sludge demanding separate investments.

The household waste polluting environment can become the energy source. However, their direct energy treatment is not always possible because of high variability of morphological composition and mechanical properties. Therefore the household waste is preliminary processed into RDF. RDF possesses lower humidity and ash content and higher combustion heat, in comparison with the primary waste.

Peat is a product of decomposition of plants and it is formed on marshes. By various estimations peat world's reserves are 270-6000 billion t [18]. Due to rather low calorific value this kind of fuel is not widely used for energy production. Currently peat attracts more interest as it is considered as the renewed energy source.

Energy properties of used car tires are close to coals. They have high calorific value and carbon containing and low oxygen content. Nevertheless the efficiency of car tires combustion is not high enough because of a low reactive capacity. Average world's rubber consumption is ~3.8 kg/man×year, approximately half of this amount is car tires [19].

Plastic waste is a part of a household waste and RDF. It can be separated into individual fraction. Besides, huge garbage islands mainly comprising plastic debris have accumulated in the world ocean. This kind of waste also can be considered as the renewed energy source. The table also tabulates the calorific value of presented kinds of waste and biomass calculated on its composition [20], as far as the published data do not always well agree with each other.

Wood is used as a fuel by millennia and is one of the most simple in use energy resources. Nevertheless, the efficiency of electricity production by wood combustion is 18-24 % [21]. The efficiency of electricity production can be increased up to ~29 % using the integrated gasification combined cycle (IGCC), and at usage of plasma gasification — to ~35 % [22]. Usage of plasma blasting allows increasing the temperature of the process, rate of physical and chemical transformations, conversion level of fuel, residence time of gases in the reactionary volume, hydrogen and carbon monoxide content in syngas, thermal stress of the reactionary volume and specific output (in ~7.8 times at increase in temperature from 1500 K to 1900K). Development of power engineering on the basis of plasma gasification is one of the most promising directions.

2. Potentially achievable energy parameters
The numerical modeling of the plasma gasification allows evaluation of the energy potential of biomass and waste using the following assumptions:

- Thermodynamically equilibrium composition of a mixture of plasma and ash-free weight of wood waste calculated at temperature 1500 K and atmospheric pressure (101.325 kPa) is assumed for ash-free composition of products of plasma gasification of biomass and waste;
- The inorganic component does not participate in chemical reactions, and power inputs on its heating from 298 K to 1500 K make up ~1.367 MJ/kg;
- There is no change in the composition of gasification products at their cooling to 298 K;
- Mass composition of air: N₂ – 75.52; O₂ – 23.14; Ar – 1.29; CO₂ – 0.05;
- Value of the specific flow rate of oxidizing agent and level of corresponding specific power inputs were selected from a condition of achievement of adiabatic combustion temperature of produced gas 2000 K;
- The specific yield of the electric power, using the produced syngas as a fuel for the combined cycle, was evaluated on the basis of dependence of the combined cycle on the temperature range 1400-2000 K [23].

The data obtained as a result of calculations (Table 2) show, that use of plasma in the course of biomass and waste gasification allows increasing the efficiency of fuel usage for electric power
production in 1.2-1.6 times (in comparison with efficiency 29% for IGCC).

### Table 2. Potentially achievable energy parameters.

| Parameter                                      | Feedstock     | Wood waste | Switchgrass | Cow manure | Chicken manure | Sewage water | Sludge | RDF | Peat | Used car tires | Plastic waste |
|------------------------------------------------|---------------|------------|-------------|------------|----------------|--------------|--------|-----|------|----------------|----------------|
| Name                                           | Units of measurement | kg/kg | kg/kg | kg/kg | kg/kg | kg/kg | kg/kg | kg/kg | kg/kg | kg/kg | kg/kg | kg/kg |
| Air flow rate                                  | Published     | 2.691     | 1.571     | 2.970     | 1.955         | -0.099       | 2.762  | 1.557 | -0.941 | 1.752 |        |        |
| Specific yield of syngas                       | Calculated    | 2.331     | 1.941     | 3.66      | 3.205         | 2.671        | 2.042  | 2.247 | 1.519 | 1.542 |        |        |
| Syngas composition                             | Nm³/kg        | 2.385     | 2.516     | 1.184     | 2.005         | 1.786        | 2.571  | 2.648 | 4.954 | 4.667 |        |        |
| Yield of steam                                 | kg/kg         | 0.278     | 0.203     | 0.321     | 0.197         | 0.139        | 0.212  | 0.154 | 0.001 | 0.091 |        |        |
| Syngas LHV                                     | MJ/Nm³        | 5.012     | 5.035     | 5.315     | 4.980         | 5.081        | 5.033  | 4.960 | 4.988 | 4.823 |        |        |
| Specific yield of chemical energy              | MJ/kg         | 11.95     | 12.67     | 6.293     | 9.984         | 9.08         | 12.94  | 13.13 | 24.71 | 22.51 |        |        |
| Specific yield of electricity minus its own internal power requirements | MJ/kg | 4.928 | 6.505 | 1.041 | 4.409 | 5.79 | 5.486 | 6.814 | 15.75 | 12.59 |        |        |

The exception is the cow manure, that is connected with its increased (in relation to other kinds of considered raw materials) humidity. Probably the same refers to sewage sludge as the specified humidity at level of 6.1 % for the given kind of raw materials can be achieved at the expense of essential energy consumption. Nevertheless, it is impossible to lose sight of these kinds of raw materials, as they are formed everywhere in enough considerable quantities, and additional drying can be organized at the expense of the excesses of heat formed at various stages of the process. It is also necessary to note, that not all specified kinds of raw materials are easily treated even by the combustion process and plasma gasification is actually a unique and simple way of energy extraction.

### 3. Survey of existing designs

A lot of companies around the world promote plasma gasification to the market. AlterNRG [24], Integrated Environmental Technology LLC [25], Advanced Plasma Power [26], Plasco Energy Group [27], Pyrogenesys Canada Inc. [28] and others achieved the better results. These companies created pilot installations of various scales. Currently, some of them are at the stage of implementation of large-scale commercial projects. The most widespread are gasification processes using molten material layer (Integrated Environmental Technology LLC), with the subsequent plasma conversion of the crude syngas (Pyrogenesys), traditional gasification in the updraft process with plasma conversion of the crude syngas (Plasco Energy Group, Advanced Plasma Power), or the updraft process of steam-oxygen gasification with plasma use for liquid slag discharge (AlterNRG).

The metallurgical furnaces with Joule heating of molten material layer are used in case of the gasification on molten layer. Wastes are fed on a melt surface. In this area either the electric arc is ignited, or the plasma jet from the plasma torch is injected. In some designs the plasma torch is
mounted in a special chamber at the outlet, providing mixture of off-gases with high-temperature oxidizing agent for conversion of tars containing in crude synthesis gas supplied from the melting chamber. Creation of large-scale installations is the advantage of the process. The second advantage is capability to remove noncombustible waste components as melt with its separation on metal and non-metal fractions. The essential disadvantage is the increase of energy consumption for melt maintenance.

The AlterNRG updraft gasification uses supply of waste product simultaneously with metallurgic coke and limestone. Plasma torches are mounted at the bottom part of the gasifier and serves for heating-up and maintenance of melt in a liquid state (the lime stone is fed to decrease the melting temperature). Oxygen is fed into the gasification zone through the special tuyeres. The produced gas is removed from the top of the gasifier. Syngas, produced in the gasification zone passing through colder upper layers of waste is polluted by tars, forming in the pyrolysis zones, evaporating water does not participate in the conversion due to low temperatures in the zones of its release. It is the essential deficiency of the updraft process. The produced gas also needs additional conversion or tar cleaning.

The common essential disadvantage of these technologies is application of free-burning arcs or DC plasma torches. Very low efficiency of energy transfer from the arc to gas ~30 % is a feature of free-burning arcs. The efficiency of DC plasma torches is about 60 % due to high losses in the power supplies.

We consider AC plasma torches to be the most efficient plasma generating systems. Plasma torches developed in IEE RAS provide the efficiency of electricity conversion into thermal plasma energy of 90-94 %. A large-scale experimental installation for plasma gasification has been created on the basis of these plasma torches in IEE RAS [29-35].

References
[1] 2012 BP Statistical Review of World Energy 2012 BP p.l.c. p 45
[2] Peters G P, Marland G, Le Quéré C, Boden T, Canadell J G and Raupach M R 2012 Rapid growth in CO₂ emissions after the 2008–2009 global financial crisis. Nature Climate Change 2, 2-4 (doi:10.1038/nclimate1332)
[3] Ladanai S and Vinterbäck J 2009 Global Potential of Sustainable Biomass for Energy (Uppsala: Swedish University of Agricultural Sciences)
[4] Green D W, Perry R H 2007 Perry's Chemical Engineers' Handbook, Eighth Edition p 2400 (McGraw-Hill, United States)
[5] Weiland N T, Means N C and Morreale B D 2012 Product distributions from isothermal co-pyrolysis of coal and biomass Fuel 94 563-570 (doi:10.1016/j.fuel.2011.10.046)
[6] Santoianni D A, Bingham M F, Woodard D M and Kinnell J C 2008 Power from Animal Waste—Economic, Technical, and Regulatory Landscape in the United States Journal of EUEC 2
[7] Giuntoli J, de Jong W, Arvelakis S, Spleiöff Hoff H and Verkooijen A H M 2009 Quantitative and kinetic TG-FTIR study of biomass residue pyrolysis: Dry distiller’s grains with solubles (DDGS) and chicken manure Journal of Anal. and Appl. Pyrolysis 85 301-312 (doi:10.1016/j.jaap.2008.12.007)
[8] Thipkhunthod P, Meeyoo V, Rangsunvigit P, Kittiyanan B, Siemanond K and Rirksomboon T 2005 Predicting the heating value sludge from Thailand by proximate and ultimate analyses Fuel 84(7-8) 849-857
[9] Raghunathan K and Bruce K R 1997 Control of Emissions from Cofiring of Coal and RDF p 25 URL: http://www.nrel.gov/docs/legosti/fy97/26036.pdf (access date: 22.06.2012)
[10] Ranieri F D, Combs L P and Falk A Y Experimental investigation of peat hydrogasification URL: http://www.anl.gov/PCS/acsfuel/preprint%20archive/Files/24_3_WASHINGTON_09-79_0064.pdf (access date: 22.06.2012)
[11] 1995 Environmental Factors of Waste Tire Pyrolysis, Gasification, and Liquefaction. Report № 1364 (California: CalRecovery, Inc.)
URL: http://www.calrecycle.ca.gov/publications/Tires/62095001.pdf (access date: 06.08.2010)

[12] Adrados A, de Marco I, Caballero B M, A. Lopez, Laresgoiti M F and Torres A 2012 Pyrolysis of plastic packaging waste: A comparison of plastic residuals from material recovery facilities with simulated plastic waste Waste Manage. 32(5) (doi:10.1016/j.wasman.2011.06.016)

[13] Barney J N and DiTomaso J M 2010 Bioclimatic predictions of habitat suitability for the biofuel switchgrass in North America under current and future climate scenarios Biomass and Bioenergy 34(1) 124–133 (doi:10.1016/j.biombioe.2009.10.009)

[14] Keoleian G A and Volk T A 2005 Renewable Energy from Willow Biomass Crops: Life Cycle Energy, Environmental and Economic Performance Crit. Rev. Plant Sci. 24 385–406 (doi:10.1080/0735268050316334)

[15] Demirbas M F 2011 Biofuels from algae for sustainable development Appl. Energy 88 3473–3480 (doi:10.1016/j.apenergy.2011.01.059)

[16] ] Ribaudo M, Gollehon N, Aillery M, Kaplan J, Johansson R, Agapoff J, Christensen L, Breneman V and Peters M 2003 Manure Management for Water Quality: Costs to Animal Feeding Operations of Applying Manure Nutrients to Land (U.S. Department of Agriculture, Economic Research Service, Resource Economics Division. Agricultural Economic Report 824, Washington)

[17] Sattho T and Yamsaengsung R 2005 Vacuum drying of rubberwood PSU-UNS International Conference on Engineering and Environment. Novi Sad, Serbia T11-3.4. p 1-5

[18] 2009 Mineral commodity summaries p 195
URL: http://minerals.usgs.gov/minerals/pubs/mcs/2009/mcs2009.pdf (access date: 22.06.2012)

[19] 2008 World Rubber & Tire, Industry Study with Forecasts for 2011 & 2016. Study #2282
URL: http://www.freedoniagroup.com/brochure/22xx/2282smwe.pdf (access date: 22.06.2012)

[20] Reed T B, Das A 1988 Handbook of Biomass Downdraft Gasifier Engine Systems v(Colorado, US, Golden: Solar Energy Research Institute) p 140

[21] Wood Biomass for Energy. URL: http://www.fpl.fs.fed.us (access date: Feb 16 2012)

[22] Rutberg Ph G, Bratsev A N, Kuznetsov V A, Popov V E, Ufimtsev A A and Shtengel S V 2011 On efficiency of plasma gasification of wood residues Biomass and Bioenergy 35(1) 495-504 (doi:10.1016/j.biombioe.2010.09.010)

[23] Ishikawa M, Terauchi M, Komori T and Yasuraoka J 2008 Development of High Efficiency Gas Turbine Combined Cycle Power Plant Mitsubishi Heavy Industries Technical Review 45(1) 15-17

[24] Alter NRG. http://www.alternrg.com/ (access date: 21 June 2012)

[25] InEnTec http://www.inentec.com/ (access date: 21 June 2012)

[26] Advanced Plasma Power. http://www.advancedplasmapower.com/ (access date: 21 June 2012)

[27] Plasco Energy Group http://www.plascoenergygroup.com/ (access date: 21 June 2012)

[28] PyroGenesis Canada Inc http://www.pyrogenesis.com/ (access date: 21 June 2012)

[29] Bratsev A N, Popov V E, S V Shtengel and A Ph Rutberg 2006 Some aspects of development and creation of plasma technology for solid waste gasification High Temp. Mat. Processes. An International Quarterly of High-Techology Plasma Processes 10(4) 549-556.

[30] Kuznetsov V A, Bratsev A N, Kovshechnikov V B, Kumkova I I, Popov V E, Shtengel S V and Ufimtsev A A 2007 Distinctive features of biomass gasification using ac plasma generators working on air 2007 IEEE Pulsed Power Conference (PPPS-2007) (Omnipress, Madison WI USA) p 1223-1226 (doi:10.1109/PPPS.2007.4652407)

[31] Bratsev A N, Glezin I L, Kovshechnikov V B, Kumkova I I, Kuznetsov V A, Popov V E, Shtengel S V and Ufimtsev A A 2007 Experimental Research of Air Gasification of Waste. The first results XXVIII International Conference on Phenomena in Ionized Gases (ICPIG
2007) (Czech Republic: Institute of Plasma Physics AS CR, Prague, July 15-20, 2007) p 1848-1851

[32] Bratsev A N, Kuznetsov V A, Popov V E, Rutberg A Ph, Ufimtsev A A and Shtengel S V 2009 Experimental development of methods on plasma gasification of coal as the basis for creation of liquid fuel technology *High Temp. Mater. Processes* **13** (2) 147-154

[33] Popov V E et al 2011 *J. Phys.: Conf. Ser.* **275** 012015

[34] Bratsev A N, Kuznetsov V A, Popov V E and Ufimtsev A A 2011 Arc gasification of biomass: Example of wood residue *High Temperature* **49(2)** 244-248 (doi:10.1134/S0018151X11010020)

[35] Bratsev A N, Kumkova I I, Kuznetsov V A, Popov V E, Shtengel’ S V, Ufimtsev A A 2011 Air plasma gasification of RDF as a prospective method for reduction of carbon dioxide emission *IOP Conf. Series: Materials Science and Engineering* **19** 012004 (doi:10.1088/1757-899X/19/1/012004)