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STEAM PLASMA GASIFICATION OF BIOMASS USING ELECTRODELESS PLASMATRONS

S. Petrov[1], **P. Stukhlyak**[2], **S. Bondarenko**[3], **S. Roshanpour**[4], **M. Ganczarski**[5]

[1]The Gas Institute of the NASU
39 Degtyarivska Str., 03113, Kyiv, Ukraine
[2]Paton Research Institute of Welding Technologies in Zhejiang Province. People's Republic of China, Zhejiang Province, Hangzhou City, Xiaoshan District, St. Shixing Beilu 857, Office 426
[3]National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
37 Prosp. Beresteiskyi, 03056, Kyiv, Ukraine
[4]Plasma Dynamics srl
11/13, Via del Progresso, Vicenza, Italy, 36100
[5]HYDROGENIUM p.s.a.
5/35, Gliniana, Lublin, Poland, 20-616

ABSTRACT

The use of plasma processes in the production of biohydrogen opens up the possibility of replacing fossil fuels with an environmentally friendly energy source from biomass. The work examines the process of plasma processing of biomass (based on the example of sunflower husks), using an electrodeless discharge to produce highly productive synthesis gas with a high hydrogen content. The use of CFD modeling made it possible to determine the parameters of a steam plasma reactor for the gasification process. The operation of the reactor is based on the principle of gasification using steam-water plasma with oxygen. The use of plasma blast allows increasing the process temperature, the rate of physical and chemical transformations, the degree of conversion of raw materials, the residence time of gases in the reaction volume, the content of hydrogen and carbon monoxide in the synthesis gas, the thermal intensity of the reaction volume and specific productivity. It has been experimentally established that plasma power affects the energy balance of the entire gasification process, and also directly affects the temperature profile, synthesis gas composition, resin yield and stability of the gasification process. The influence of such parameters as the plasma energy to waste energy ratio (PER), equivalence ratio (ER) and steam to oxygen mass ratio (SOMR) on the gasification process was studied. It has been found that increasing PER raises the average temperature of the supplied steam-oxygen mixture and increases the heat input for gasification. A dual influence of ER on the gasification process has been noted: on the one hand, a higher ER provides more chemical heat during combustion, which has a beneficial effect on the synthesis gas output, and on the other hand, a higher ER provides an increase in the amount of combustion products in the reactor, which leads to reducing the amount of flammable gases. It has been determined that with an increase in SOMR from 2 to 2.5, the volume fraction of H_2 in the synthesis gas increases, and CO_2 decreases. Hydrogen obtained from biomass gasification processes is one of the promising methods for alternative hydrogen production from fossil fuels.

KEYWORDS: electrodeless plasmatron, gasification, steam plasma reactor, biomass, CFD modeling

INTRODUCTION

Research into plasma gasification of biomass is being conducted as a response to the need for more efficient use of biomass to produce energy and various products. The growing production of advanced bioenergy carriers and biomaterials is increasing competition for various applications of biomass. Biomass is an umbrella term that includes many sources such as agricultural, aquatic, and land waste. In order to develop the use of biomass in a sustainable manner, the status and prospects of biomass value chains for heat, power, fuel and materials production are reviewed, their current and long-term levelized production costs and avoided emissions are assessed. Currently, the economically and environmentally preferred options are the combustion of wood chips and pellets in district heating systems and large-scale fermentation. The key technologies for biomass processing are large-scale gasification (bioenergy and biomaterials) and fermentation (biofuels and biomaterials). However, both methods require improvement of technological and economic indicators. In the last decade, the use of biomass to produce modern bioenergy and biomaterials has increased significantly to counter the depletion of fossil resources and reduce greenhouse gas emissions. This growth is expected to continue or even accelerate [1]. The growing demand for biomass will increase competition between biomass feedstocks and applications. Thus, to ensure sustainable expansion of biomass use, it is necessary to know which pathways (biomass value chains) are the most promising for the production of heat, electricity, fuels and materials in terms of their technological, economic and environmental performance. Among the various thermochemical processes for processing biomass, the most developed are pyrolysis and gasification.

In this regard, the production of low-carbon hydrogen for use as a clean energy carrier is an important step towards a decarbonized economy. Plasma pyrolysis is an emerging technology that has great potential for large-scale production of low-carbon, affordable hydrogen. Achieving the ambitious emissions reduction targets set in the Glasgow COP26 agreement [2] will ensure the transition to a zero-carbon circular economy. Today, 96 % of hydrogen is produced from fossil fuels through reforming. The most common processes include steam methane reforming (48 %), petroleum and heavy oil reforming (30 %), and coal gasification (18 %). All these processes result in the release of large amounts of CO_2. Low-carbon (or zero-carbon) methods of hydrogen production are needed to create a sustainable and clean hydrogen economy. One of the attractive methods for processing hydrocarbons is the use of plasma. The plasma system can be adapted to work with various hydrocarbons. Today, due to the high demand for energy consumption, limited fossil fuel resources, staggering energy costs and negative environmental impacts, scientists are constantly looking for innovative and low-cost methods to transition from fossil fuel consumption to sustainable, efficient, green and renewable energy sources. In this regard, the conversion of biomass to hydrogen (H_2) using plasma is increasingly attracting attention due to its advantages over traditional energy sources [3]. Currently, biomass provides about 14 % of global energy demand. However, the cost of producing hydrogen from biomass remains relatively high and ranges from $1.21 to $2.42/kg for gasification and $1.21–2.19/kg for pyrolysis, which is three times the cost of steam methane reforming (0. 75 $/kg) [4].

The emergence of new plasma technologies in thermochemical conversion methods may open new routes to the cost-effective production of H_2 and value-added products. Plasma pyrolysis is an emerging technology that has great potential for large-scale production [5–7]. Despite all the unique advantages of plasma technologies for H_2 production, it is necessary to eliminate the weaknesses and gaps that hinder their application on a large scale [8]. These are incomplete conversion, low energy efficiency, unwanted by-products and lack of scalability, which are the main obstacles in H_2 production using plasma technologies.

Microwave discharge is one of the techniques used to produce nonequilibrium plasma, in which, even at atmospheric pressure, the temperature of electrons is approximately 4000–6000 K, while the temperature of heavy particles is about 2000 K. When using steam as a plasma-forming gas in microwave discharge, radicals such as H, OH and O are generated, as well as high-energy electrons. Due to the high electron density, the working gas in a microwave plasma is highly dissociated and therefore chemically very reactive. The plasma creates both reducing and oxidizing conditions, which indicates the effectiveness of steam plasma for various types of material processing. Microwave gasification is a new technology, but it is certainly a promising technology for achieving a sustainable bioeconomy [7]. Although this technology shows enormous potential that can be fully realized in the near future, the selectivity and efficiency of biohydrogen production and gas synthesis still require improvement and further research to ensure cost-effective and energy-saving industrialization.

Three different types of advanced thermal plasma technologies such as DC atmospheric plasma torches, RF plasma torches and microwave plasma torches are considered for small and industrial scale waste treatment. The authors of [9] conducted a comparative study of all three plasma torches for use in the energy sector and waste recycling. Simulation modeling and experimental results of indirect DC plasma torch and high frequency plasma torch were presented. The results show that DC plasma torches and high frequency plasma torches are economical and beneficial for large-scale waste treatment and energy recovery. At the same time, when processing waste on a small scale, a microwave plasma torch can be used. Overall, minimizing environmental impact and process economics are the most important parameters to improve the feasibility and sustainability of plasma waste treatment plants. High-frequency plasma torches with plasma power from 15 kW to 200 kW are designed for more than 10,000 hours of non-stop operation [11]. They are widely used in the chemical and metallurgical industries due to their high reliability and long service life without replacing parts (within 2–3 months).

The use of thermal plasma torches for waste treatment is gaining momentum worldwide due to their suitable basic characteristics [9]. Plasma gasification has so far been developed commercially, typically using DC plasma discharge technology [10]. However, DC burners suffer from short electrode life in the presence of oxidizing gases, resulting in high operating costs associated with their replacement. An alternative is to use electrodeless plasma torches.

PURPOSE AND OBJECTIVES OF THE STUDY

The goal of this study was to generate atmospheric pressure plasma (a mixture of water vapor and oxygen) using an electrodeless discharge for the processing of biomass to produce hydrogen.

To achieve this goal, it is necessary to solve the following tasks:

1. Conduct CFD modeling of the process of plasma gasification of biomass using a mixture of water vapor and oxygen.

2. Develop and implement a special reactor system that allows for environmentally friendly and complete plasma-thermal gasification of biomass.

3. Investigate the efficiency of producing synthesis gas with a high hydrogen content using the developed reactor system.

METHODS OF RESEARCH

Considering the knowledge gaps in scaling up steam plasma gasification technology, this study developed a microwave-assisted and induction-assisted continuous steam-oxygen gasification system and explored the feasibility of using them to produce hydrogen-enriched synthesis gas. A review of the literature shows that there is currently no information about such technology in the open literature.

The main part of the process plant for the continuous production of hydrogen-rich synthesis gas is the steam-plasma gasification reactor. Synthesis gas consists mainly of CO, H_2, CO_2 and H_2O. The reactor being developed by the authors is intended exclusively for gasification of biomass, namely sunflower husks. Sunflower husks contain of 81 % volatile substances, which means they are suitable for various thermochemical processes. Structurally, the reactor is designed to be scalable. The operation of the reactor is based on the principle of gasification using plasma of a mixture of water vapor and oxygen. In the reactor, the biomass is converted into synthesis gas, the composition of which reflects thermodynamic equilibrium at a temperature in the upper part of the reactor of about 1000–1200 °C. An effective gasification process requires achieving high temperatures, which are provided by plasma heating and reducing the proportion of ballast through the use of steam-oxygen blast. Gasification using oxygen-enriched blast leads to an increase in the temperature and speed of the process, which brings it closer to the conditions of thermodynamic equilibrium. The energy supplied with the plasma is spent on maintaining the temperature of the process, compensating for the decrease in heat generation from the oxidation of the raw material. The shaft-type reactor is shown in Figure 1, *a*. It consists of a gasification chamber (removal of volatile substances) and gasification of fixed carbon in the coke residue after removal of volatile substances. The composition of the synthesis gas at the outlet of the reactor is considered as the sum due to the conversion of solid carbon and pyrolysis gases. At the bottom of the chamber there are tangential channels for supplying a mixture of water vapor and oxygen at a temperature of about 2000 °C. Gasification of husks is carried out in a vortex chamber in a rotating high-temperature flow. The chamber has a shape close to the cylindrical one.

The vortex plume (Figure 1, *b*) uniformly fills and heats the surface of the chamber. Thus, the speed and completeness of gasification increase. The entire internal surface of the reactor is made of special heat-resistant ceramics designed to operate in aggressive conditions. The design of the reactor is based on CFD modeling (Figure 2, *a*, *b*).

The synthesis gas leaving the reactor (see Figure 1) has a very high temperature (about 1000 °C). Heat recovery from synthesis gas using a radiative/convective heat exchanger increases the overall efficiency of the process. The heat is used to produce process steam and energy recovery. The use of a thermally insulated reactor reduces losses and entrainment of fly ash residues. This allows the reactor to be put into long-term operation without stopping for cleaning. The location of the vortex in the chamber promotes self-cleaning of the chamber walls from deposits with a flow of fresh steam-oxygen mixture. Ash is removed through a movable grate. Through it, oxygen is supplied to the gasification zone. This allows the process to be carried out in conditions below the temperature at which the ash begins to deform (1140 °C) and to

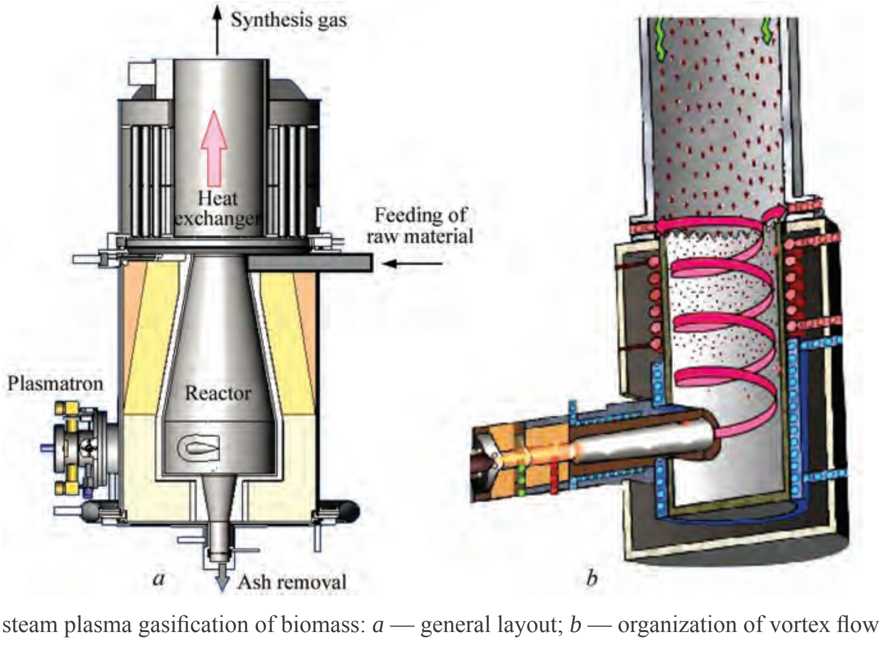

Figure 1. Reactor for steam plasma gasification of biomass: *a* — general layout; *b* — organization of vortex flow

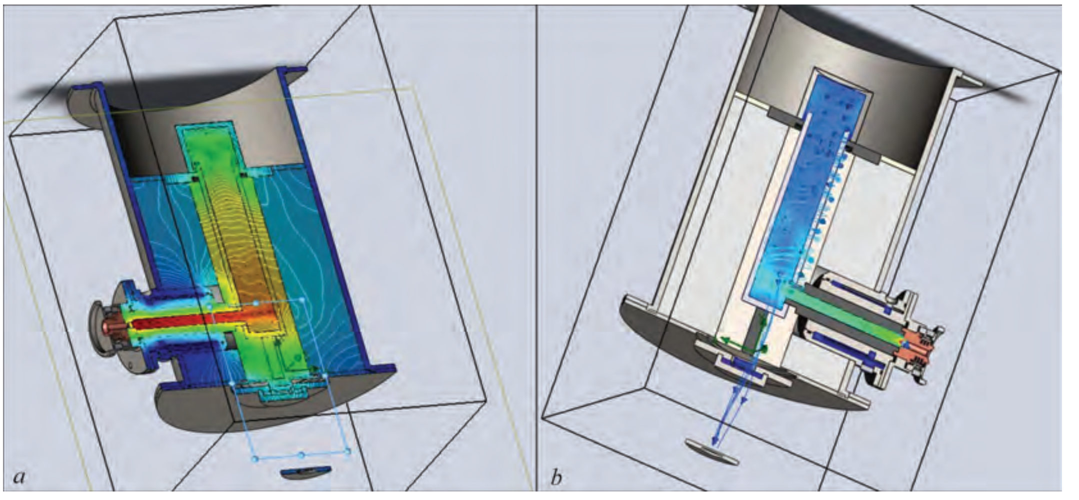

Figure 2. Simulation of a steam plasma reactor: *a* — temperature fields; *b* — velocity fields

build a gasification regime with the removal of solid slag. At the first stage of the process, raw materials are unloaded into a storage hopper. The volume of the hopper is sufficient to dampen fluctuations in waste reception cycles. From the hopper, waste is fed into the upper part of the reactor using a screw feeder.

The most important aspect in developing technologies for the production and use of synthesis gas is the relationship between its composition and energy cost. Since we strive for the highest productivity, which is also the most economical option, the method developed by the authors to reduce specific power consumption is based on the use of the plasma-autothermal principle of gasification of biomass (sunflower husks, corn cobs, etc.). First, gasification of the biomass occurs with the release of volatile products under steam-oxygen plasma conditions and subsequent combustion of part of the gasification products to CO_2. Here, 33173 kJ/kg of carbon is released. This heat, together with the plasma heat, is sufficient to compensate for the endothermic effect (10875 kJ/kg of carbon) of the water-gas reaction ($H_2O + C = C + H_2$) of biomass gasification, which occurs in a steam environment and amounts to 8 kW·h/kg of carbon.

The results obtained by the authors [12] indicate that the gasification process provides ideal thermodynamic conditions for gasification reactions with various fuels. The process can operate in a quasi-equilibrium state without the use of catalysts at a temperature of 1273 K. An important overall result is the fact that the concentrations of H_2 and CO increase with increasing O_2 consumption until the O_2/fuel ratio becomes equal to 0.60–0. 70. At the same time, the concentrations of H_2 and CO have maximum values (44 and 24 mol.%), respectively (Figure 3, *a*).

An increase in O_2 consumption promotes exothermic combustion reactions and, therefore, leads to an increase in temperature in the reactor (Figure 3, *b*). Therefore, to obtain richer synthesis gas, low oxygen consumption and acceptable reactor temperature, it is better to choose an O_2 flow rate at which the O_2/fuel ratio is in the optimal region.

The effect of steam supply on the composition of the synthesis gas and the temperature in the reactor in the absence of additional heating is shown in Figure 4. Figure 4, *a* shows that an increase in steam flow leads to a moderate decrease in the concentrations of H_2 and CO. When the H_2O/O_2 ratio increases by 200 %, the H_2 and CO concentrations decrease from 3 to 9 %,

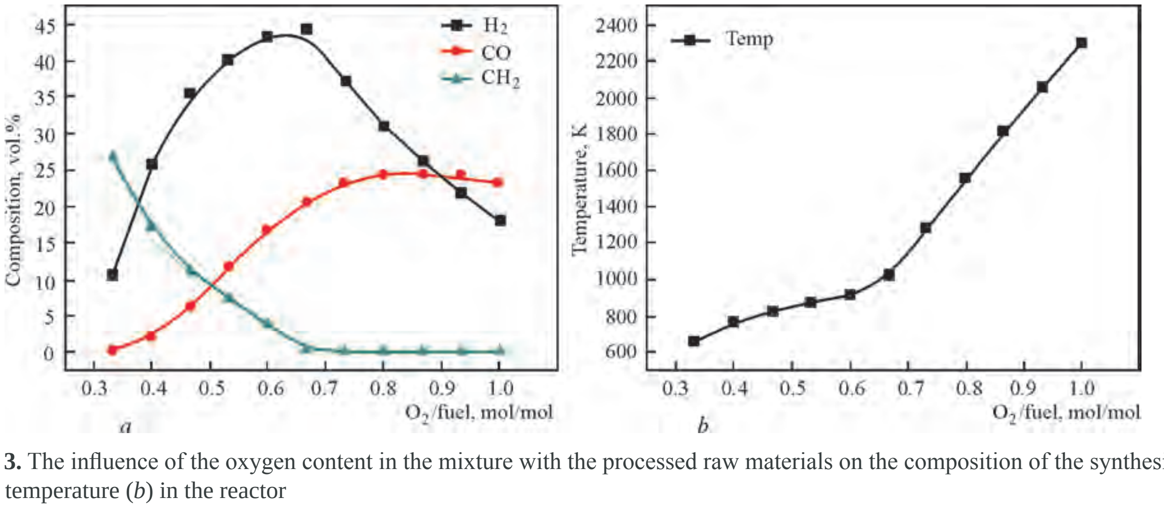

Figure 3. The influence of the oxygen content in the mixture with the processed raw materials on the composition of the synthesis gas (*a*) and temperature (*b*) in the reactor

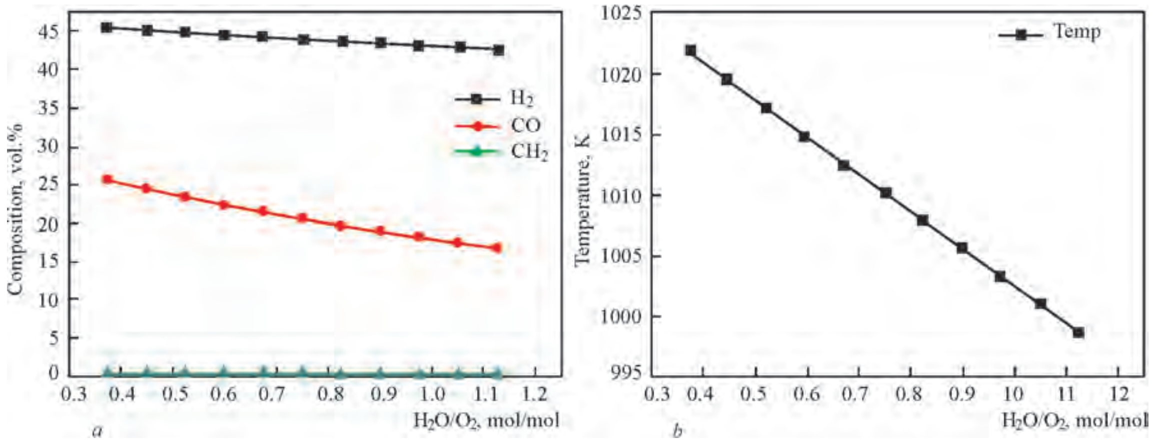

Figure 4. The influence of steam content in the feedstock on the composition (*a*) of synthesis gas and temperature (*b*) in the reactor

respectively. This may be due to the fact that the increased amount of steam takes away some of the heat and reduces the temperature of the reactor, as shown in Figure 4, *b*, thereby preventing the endothermic reactions of steam reforming and gasification.

The main role of additional plasma heating of the working mixture in the reactor during gasification becomes clear from Figures 3 and 4.

RESEARCH RESULTS

Atmospheric pressure plasma jets are the main tool for gasification. However, the small size of atmospheric pressure plasma jets limits their use to small-scale processes in materials processing. To solve this problem, the authors have developed a method for increasing plasma volume without additional power supplies or circuits. In this case, additional gas flows are located orthogonal to the direction of jet propagation, which leads to the formation of new plasma regions along these flows. This approach increases the volume of the plasma, which also increases the effective area available for interaction with surfaces. The resulting expanded plasma flows are recorded using methods of visualization and optical emission spectroscopy with time integration, as well as by calculation. This method is attractive for effective exposure of large areas to plasma. Figure 5 shows the results of modeling and full-scale tests of increasing the volume of plasma jet flows.

The main processes in the reactor (see Figures 1 and 2) are as follows. The carbon residue from the pyrolysis zone meets and reacts with gasifying agents. At the same time, homogeneous reactions occur in the gas phase. When high-temperature steam is supplied to this section, as we did during testing, the reaction system becomes more complex. First, injection of high temperature steam activates the water shift reaction, which significantly affects the chemical equilibrium in this section. Secondly, the introduction of additional mass and energy affects the mass and energy balances inside the reactor. It is impossible to accurately model all the reactions that occur in this zone. High-temperature plasma injection of oxygen and steam is a critical component of the process. Plasma power affects the energy balance of the entire gasification process and directly affects the temperature profile, synthesis gas composition, tar yield suppression and stability of the gasification process.

The experimental test was carried out in a laboratory gasifier (Figure 6), developed in accordance with CFD modeling (Figure 2). Thermal insulation of the reactor ensures an efficiency of more than 75 %. The useful power of the plasma torch is 10–30 kW. Husk consumption is up to 50 kg/hour: it contains: ash —

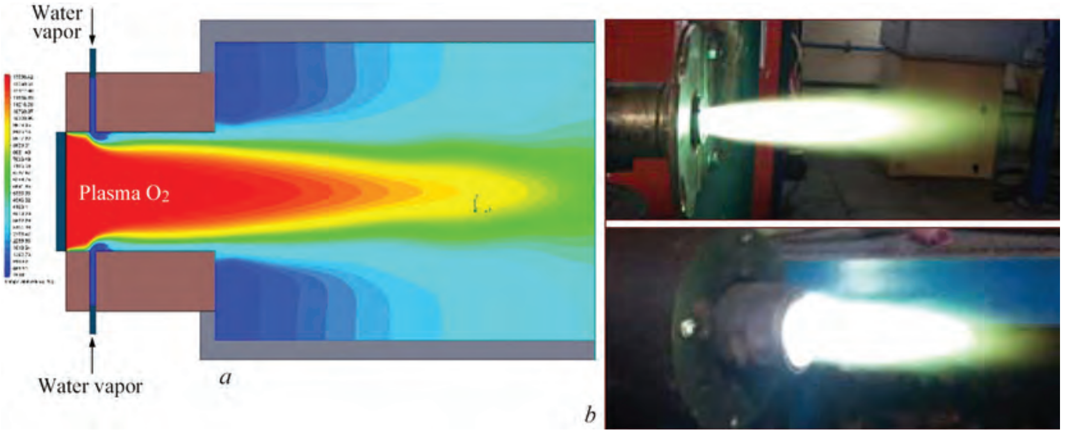

Figure 5. Increasing the volume of plasma jet flows: *a* — modeling; *b* — full-scale tests

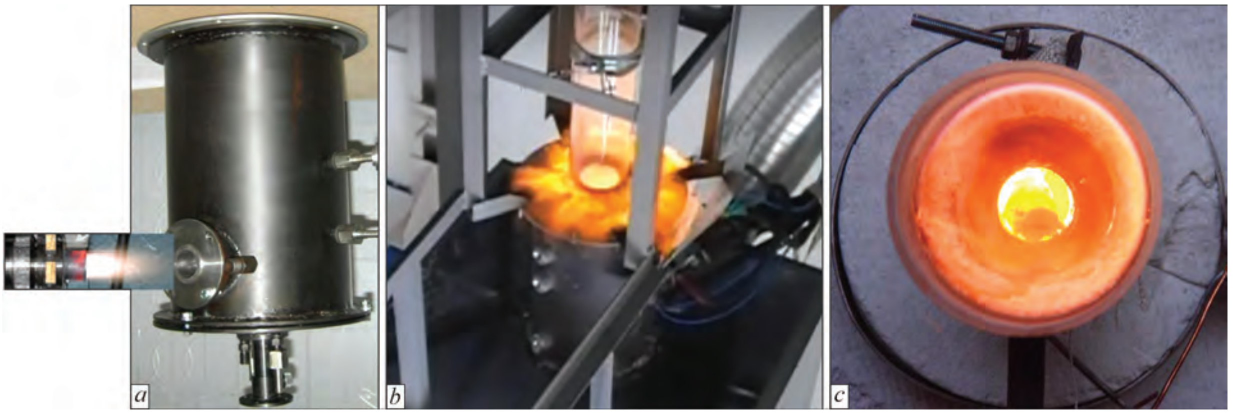

Figure 6. Demonstration vortex vapor-plasma reactor: *a* — external view; *b*, *c* — reactor in operation. Test materials: sunflower husks and corn cobs

up to 1.5 kg/hour, nitrogen — up to 1.5 kg/hour, moisture — up to 3.5 kg/hour. The lowest calorific value of sunflower husk is 17–19 MJ/kg or up to 5 kW/h. Bulk density is 100–150 kg/m^3. Steam consumption is 2–7 kg/hour, oxygen consumption is 1–3 kg/hour. Stoichiometry is 1.45 kg O_2 per 1 kg of husk.

The peculiarity of sunflower husk is its high yield of volatile substances (≈ 80 %), it is well gasified. Fixed carbon is 22.8 %. However, the composition of husk ash contains an increased amount of alkali metal oxides, calcium oxides (CaO), silicon (SiO_2), aluminum (Al_2O_3), etc. The presence of low-melting eutectics in the dust and slag causes increased slagging of both radiation and convective heating surfaces. This imposes serious restrictions on the organization and parameters of the process. The slag capacity of the ash should be taken into account. It increases with temperature. The softening temperature of ash, due to the presence of up to 15 % CaO and alkali metal oxides in the composition, is quite low and already at a temperature of 850–900 °C, slagging of heating surfaces becomes avalanche-like. Therefore, gasification of husks requires a low-temperature regime [13].

In this study, by analogy with work [14], test materials (sunflower husks) and dimensionless characteristic numbers were used to characterize the operating parameters of oxygen-steam plasma gasification. The plasma flow (Figure 5) provides heat for gasification in the reactor (Figure 6). The amount of plasma heat is characterized by the ratio of plasma energy to waste energy (sunflower husk) (PER), which is defined as:

$$PER = \frac{P_{pla}}{LHV_w \cdot \dot{m}_w},$$

where P_{pla} is the plasma power; LHV_w is the lower calorific value of raw materials; $\dot{m}_w$ is mass flow of raw materials.

Equivalence Ratio (ER) is used to quantify the degree of combustion in gasification/processes:

Table 1. Measurement results

Experiment number	1	2	3	4	5	6	7
Operating parameters							
PER	0.12	0.08	0.04	0.12	0.12	0.12	0.12
ER	0.06	0.06	0.06	0.04	0.08	0.06	0.06
SOMR	2.26	2.26	2.26	2.26	2.26	2.0	2.5
Steam temperature, °C	1500	1100	800	1800	1300	1600	1250
Measurement results							
Synthesis gas output, nm^3/kg waste	1.67	1.4	1.2	1.57	1.77	1.66	1.7
H_2 volume fraction, %	55	45	30	57	52	50	55
CO volume fraction, %	32	30	25	35	30	30	35
CO_2 volume fraction, %	10	18	30	6	16	8	8
N_2 volume fraction, %	2	2	2	2	2	2	2
CH_4	0	5	13	0	0	0	0
H_2/CO	1.72	1.5	1.2	1.63	1.73	1.67	1.57

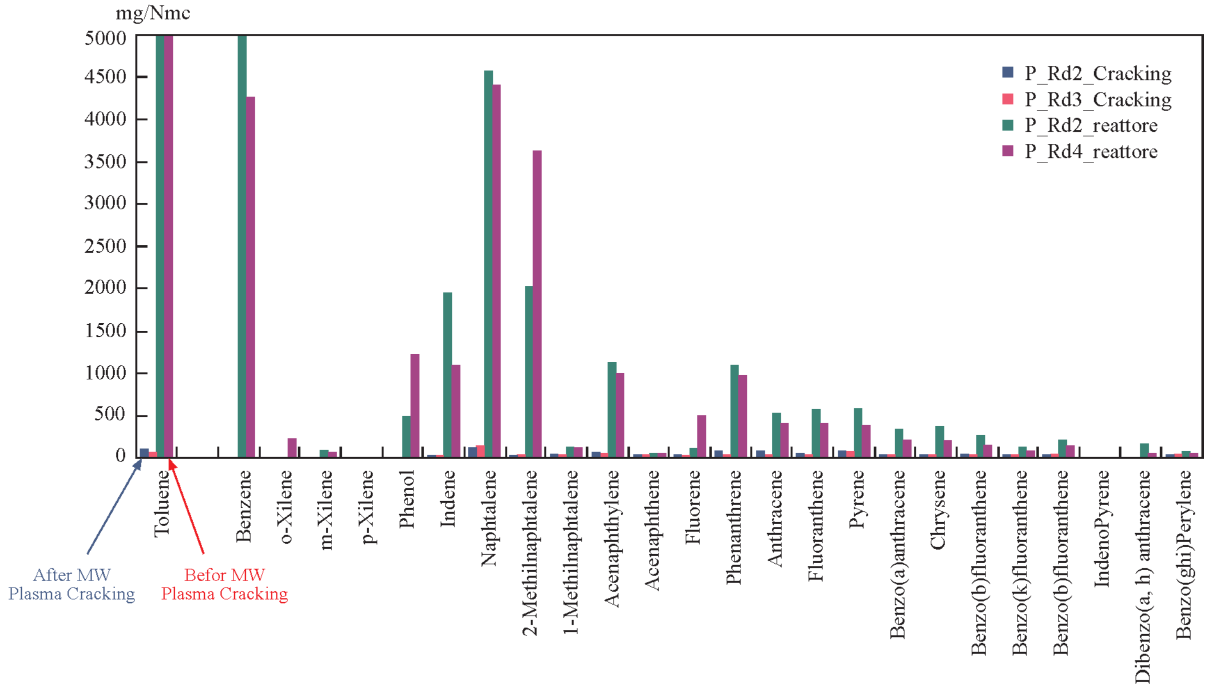

Figure 7. Gas chemical analysis of wood chip pyrolysis. Amounts of components before and after plasma molecular cracking [17]

$$ER = \frac{\left(\dot{m}_{O_2} / \dot{m}_w\right)}{\left(\dot{m}_{O_2} / \dot{m}_w\right)_{stoik}},$$

where $\dot{m}_{O_2}$ is the oxygen consumption; $\dot{m}_{O_2} / \dot{m}_w$ is the ratio of oxygen and raw material consumption; $\left(\dot{m}_{O_2} / \dot{m}_w\right)_{stoik}$ is the stoichiometric ratio of oxygen and raw material consumption.

The steam to oxygen mass ratio (SOMR) is a dimensionless parameter, which is used to characterize the steam flow rate in the oxygen-steam gasification process. In this work, it was used as the third dimensionless parameter:

$$SOMR \quad \frac{steam}{\quad}$$

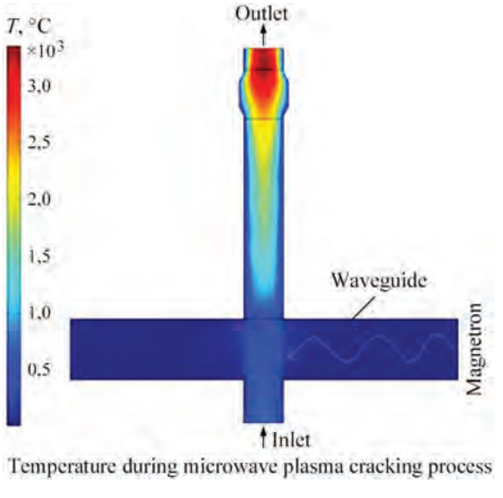

Figure 8. Simulation of microwave plasma. Gas temperature distribution inside the plasmatron

The results of measurements of plasma steam-oxygen gasification of sunflower husks in a demo reactor (Figure 6) are given in Table 1.

High-temperature plasma blasting is the most important component of the process. Plasma power affects the energy balance of the entire gasification process, and it also directly affects the temperature profile, synthesis gas composition, resin yield and stability of the gasification process. Several cases were simulated to investigate the influence of PER on gasification performance. In these cases, the ER and SAMR values are set to 0.06 and 2.26, respectively. These values have been verified as "optimal" values for oxygen and steam gasification. The PER value ranges from 0.04 to 0.12. Increasing PER increases the average temperature of the steam-oxygen feed mixture and increases the heat input for gasification. The volume fractions of all combustible gases increase with increasing PER, while the opposite trend is observed for CO_2. However, it should be noted that the positive effect of increasing PER is not unlimited. The temperature inside the reactor also increases with increasing PER. Too high a temperature compromises the thermal stability of the reactor walls, and low-melting ash components may melt in the gasification section. An average wall temperature in the gasification section of more than 1300 °C is already too high for engineering applications.

In traditional gasifiers, the energy required for heating the feedstock, pyrolysis and gasification of the feedstock is generated mainly through partial combustion. The equivalence ratio (ER) for a traditional gasifier is around 0.3 to meet the energy demand. In the case under study, heat is introduced by plasma and high-temperature steam, so the ER val-

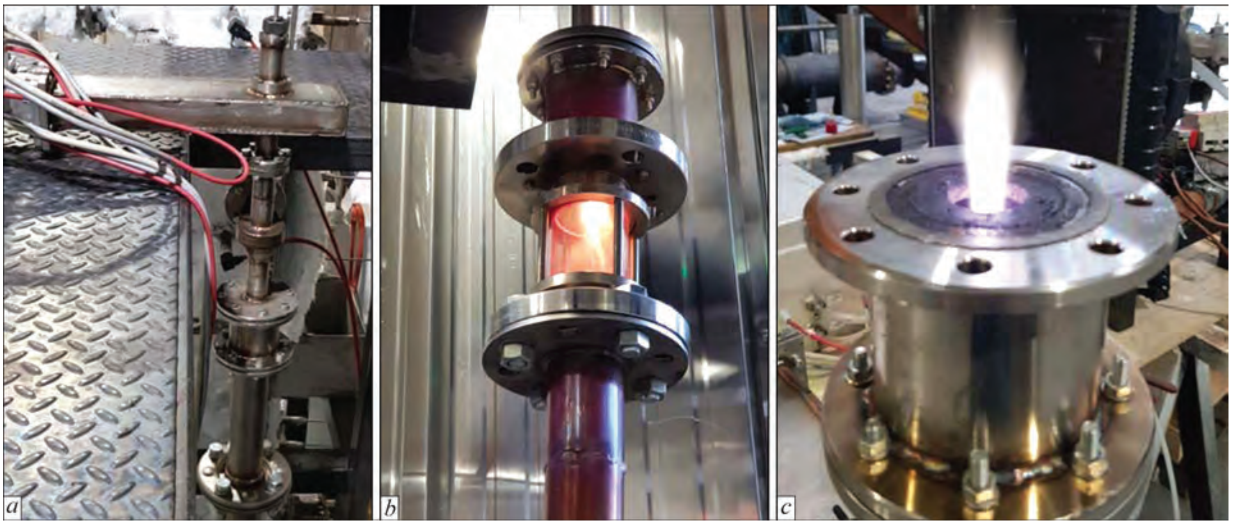

Figure 9. Microwave plasma system (*a*) on a pyrolysis reactor (*b*), microwave plasmatron in the laboratory (*c*) [17]

ue will be much lower (about 0.06). The effect of ER on the gasification process is twofold. On the one hand, a higher ER provides more chemical heat during combustion, which has a beneficial effect on both the synthesis gas yield and the LHV value, so this ER effect is positive. On the other hand, a higher ER means more combustion products in the reactor, resulting in less combustible gases. When air is used, increasing the amount of N_2 entering the reactor dilutes the combustible gas content. From this point of view, ER also has a negative impact on synthesis gas production. The final impact of ER on the gasification process is a combination of these two aspects. The supply of high-temperature steam affects the gasification process from two sides. Firstly, steam is involved in chemical reactions such as the water-gas reaction and the water gas shift reaction. In this case, it affects the chemical equilibrium in the system. Secondly, high-temperature steam changes the overall flow of mass and energy within the reactor and affects the energy balance of the system. As SOMR increases from 2 to 2.5, the volume fraction of H_2 in the synthesis gas increases, and CO_2 decreases. Similar trends were noted by other researchers [14–16]. This phenomenon is the result of stimulating the water-gas shift reaction ($CO + H_2O \rightarrow H_2 + CO_2$) by increasing the steam supply. As a result of the additional heat input from high-temperature steam, the synthesis gas yield and LHV slowly increase with increasing SOMR.

Pyrolysis gas formed during biomass gasification in traditional gasifiers is highly contaminated and contains resins and many other heavy hydrocarbons (Figure 7). The direct use of pyrolysis gas is complicated by the presence of aromatic substances in its composition. This gas is not suitable for combustion (due to environmental regulations) or as fuel for electric generators (due to engine failure).

The traditional purification (cracking) of such gas (pyrolysis gas from wood chips or sunflower husks) is thermal cracking, but this method requires high energy consumption (about 360 kW/h per 1000 N·m^3/h), which is not economically feasible [17].

Therefore, for this task there is a new cracking technology — microwave plasma cracking.

Gas pyrolysis cracking processes will make it possible to prepare raw gas to power heating and hot water boilers or use it as fuel for gas generating stations in accordance with modern environmental requirements.

An important task is the cracking of pyrolysis gas and the conversion of resinous substances (resins, tars, aromatic molecules) into a gaseous state, thereby increasing the energy value of the gas. The results of the microwave plasma simulation are shown in Figure 8.

According to the results obtained by the Italian company Plasma Dynamics SRL [17], energy consumption during microwave plasma cracking of pyrolysis gas from wood chips is about 75–80 kW/h per 1000 N·m$_3$/h), which is economically acceptable. The microwave plasma system is shown in Figure 9.

Synthesis gas by components (vol.%) after plasma cracking has the following composition: hydrogen (H_2) — 45; carbon monoxide (CO) — 20; carbon dioxide (CO_2) — 14.5; methane (CH_4) — 12; aqueous phase (H_2O) — 6.3; nitrogen (N_2) — 0.99; ethane (C_2H_6) — 0.5; ethylene (C_2H_4) — 0.5; acetylene (C_2H_2) — 0.2; oxygen (O_2) – 0.01.

CONCLUSIONS

1. A new model of biomass gasification using electrodeless HF and microwave plasmatrons and steam-oxygen blast has been developed and studied.

2. The influence of three dimensionless operating parameters PER, ER and SOMR is discussed:

- PER has a positive effect on both synthesis gas yield and LHV synthesis of gas with suppression of tar formation.
- ER has two contradictory effects on LHV synthesis of gas: a positive effect due to the increase in

chemical heat and a negative effect due to the combustion of synthesis gas.

● SOMR mainly affects the equilibrium of the water-gas shift reaction during the gasification process.

Superheated steam supplies some heat for pyrolysis, so SOMR also has a small positive effect on synthesis gas and LHV yields. There is a relationship between PER and ER. The available degree of PER and ER is determined under oxygen-steam plasma gasification conditions. The possible range for PER under the conditions studied is 0.04–0.12. The available range of SOMR and ER is defined at PER = 0.06. Increasing SAMR expands the available ER range. The optimal gas synthesis rate can be obtained at SAMR = = 2.26 and ER = 0.06.

It has been established that all three parameters have a positive effect on the efficiency of steam-oxygen plasma gasification of biomass without the formation of tars.

3. A new method for increasing plasma volume without additional power sources or circuits for effective plasma exposure over large areas has been proposed and tested.

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ORCID

S. Petrov:0000-0003-0373-8003,
P. Stukhlyak: 0000-0001-9067-5543
S. Bondarenko: 0000-0001-9590-4747,
Shahram Roshanpour: 0000-0002-4272-9217
M. Ganczarski: 0009-0002-2967-6795

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

S. Petrov
The Gas Institute of the NASU
39 Degtyarivska Str., 03113, Kyiv, Ukraine.
E-mail: vizana.sp@gmail.com

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