PLASMA-ASSISTED “WASTE-TO-ENERGY” PROCESSES

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The environmental safety and energy efficiency of the processes of alternative gaseous fuels production based on the conversion of biomass waste using plasma-steam technology are discussed. The plasma-steam installation for waste processing, that eliminates the risk of dioxins and furans production in the process of gasification is briefly described. The problems of minimization nitrogen oxides emission as well as exception into the environment of heavy metals are discussed. It is shown that the proposed variant of the processing technology correspond to the general idea of numerous publications in the world scientific literature, known as the Waste to Energy.

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INTRODUCTION

This article is an expanded version of the survey report, presented at the recent Conference on Plasma Physics and Controlled Fusion [1].

In the last few decades, the interconnected problems of the production of alternative synthetic gaseous fuels via reforming of carbon-containing materials and utilization of hazardous wastes by means of plasma technologies were widely discussed in the scientific literature [2 - 13]. In the cases of municipal solid waste utilization or processing of hazardous wastes containing carbon, the latter is converted into synthesis gaseous fuel – mixture CO and H_2. It can be used to make the facility energetically self-sufficient or as a separate fuel to commercialization of the project.

Overall, after the world's energy crisis of the 70's, a rational use of energy resources has become an essential part of the modern energy consumption culture. Technologies which use renewable raw materials are presented in its arsenal as well.

1. WASTE AS RENEWABLE SOURCE OF ENERGY

There’s a problem of using some types of renewable energy, for example, ordinary municipal solid waste as energy source nowadays. Earlier, they have been used for the heat production by means of direct combustion processes. Modern technologies don’t use them at all, due to the danger of dioxins and furans formation, in case of chlorinated raw material processing. These compounds are among the most toxic ones – their maximum permissible emission to the atmosphere in the refinement products can’t exceed 10^{-10} g/m^3 [14].

Currently, this problem is adjusted by the Directive 2000/76/EC [14]. Accordingly, the temperature should be maintained at 1100 °C in case of incineration of waste containing more than 1 % wt. of halogenous organic substances under conditions of chloride. Each local volume of gas produced in the processing has to be kept at this temperature over time ≥ 2 s. In many countries, as former countries of the USSR, where the level of chlorine in the waste is unknown beforehand, other technologies can’t be applied at all, apart from those satisfying the above requirements of the Directive 2000/76/EC. This Directive is directly related also to the technologies of medical waste processing, at least, in those countries, where medical materials still contain chlorinated components.

Another problem is if the waste contains in its composition heavy metals; incineration leads to the formation of ash, which is itself a hazardous waste. The latter environmental hazard is particularly dangerous in the case of recycling the sewage sludge of urban wastewater treatment plants.

2. PLASMA EQUIPMENT FOR MEDICAL WASTE PROCESSING

During last decade, the equipment for medical waste processing as well as another hazardous waste has been built by the Gas Institute of the National Academy of Sciences of Ukraine (NASU) and the E. O. Paton Electric Welding Institute, NASU [5, 9, 11] (Fig. 1). Its fundamental advantage is using of water steam plasma as a gasification agent which allows to obtain the gasification products of maximum calorific value. Mode of the equipment operation meets all the requirements of the Directive 2000/76/EC mentioned above and, thus, it is environmentally friendly in terms of the dioxins formation during the processing of the chlorinated waste.

Technologically, the conversion process is carried out in a flow reactor (see Fig. 1,a). It has a metal case and is lined with the layer of fireproof and heat-insulating materials on the inside.

Arc plasma torch is key element of this equipment. It was made according to the two-electrode axial scheme with hollow copper electrodes – the hollow blind cathode and the anode exit nozzle with a ledge is used. Arc cathode area affixment stabilization in the cathode hollow is realized by the solenoid magnetic field sequentially powered with an electric arc. Arc anode area affixment stabilization is realized in gasdynamic way through the anode-nozzles channel ledge and the solenoid magnetic field. The electric arc column is stabilized along the arc channel axis in the area of minimal pressure of plasma forming gas vortex. Compressed air and steam are used as the working gases. Plasma torch ignition is carried out with air and then

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transition to steam occurs after the heating (which takes at least 8 seconds). Water is used in order to cool the plasma torch.

Plasma torch electrical power reaches up to 160 kW, the arc current is up to 350 A, the efficiency coefficient equal 0.71. The power supply voltage is 500 V. Fig. 1,b shows the appearance of the plasma torch and plasma jet generated by it, during the unit adjustment.

Fig. 2 shows the operation principle of equipment. The high temperature dense plasma effuses through a hollow anode nozzle as a stream, into the internal space of the reactor. As the result of mixing with the other ingredients of the gasification process, they all are getting the same temperature as the working volume of the reactor.

The lock-chamber for the periodic load of the packed medical waste is located in the upper part of the reactor. Unit management does not involve the full loading of the total reactor space with wastes. It is exactly the opposite, there should be free space above the in-process wastes, the volume of which can be estimated on the example of cellulose steam gasification basis - a typical component of medical waste:

$$C_6H_{10}O_5 + H_2O = 6CO + 6H_2. \qquad (1)$$

It is easy to determine that the average volume production of the gases at the 50 kg cellulose treatment per hour at the temperature of 1200 °C will be 0.124 m^3/s. On this basis, the necessary volume of the reactor free space and the gas flue, which has to exceed the second volume production by more than two times is determined. Moreover, in all the points of this volume, the temperature should be above 1100 °C. In order to control it, the reactor volume is equipped with temperature sensors.

a

b

Fig. 1. Pilot equipment for processing medical waste with productivity of 50 kg/h (a) and the water-steam plasma torch in the process of equipment setup (b)

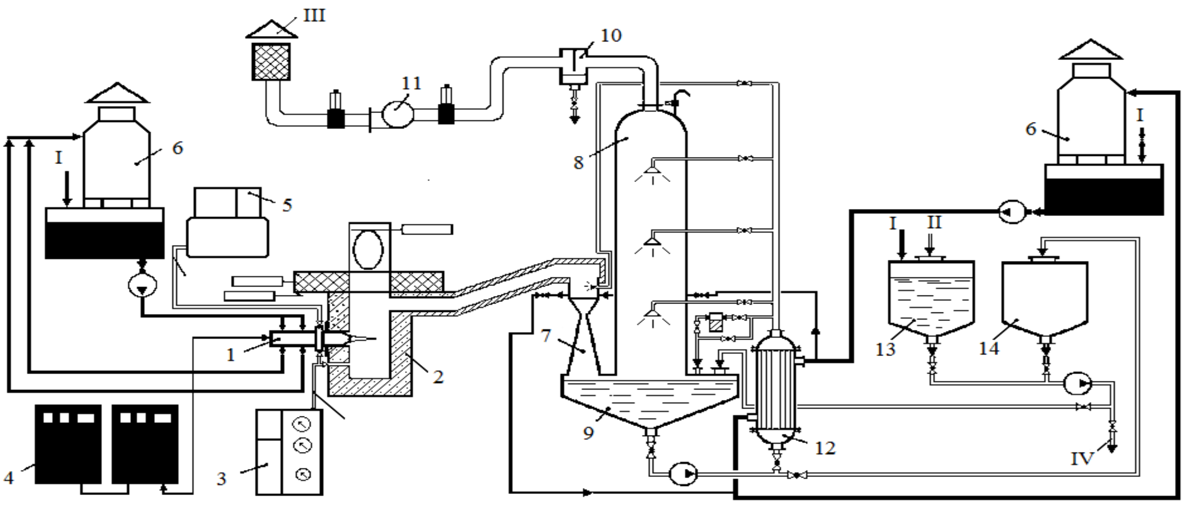

Fig. 2. Technological scheme of plasma-steam equipment: 1 – plasma torch; 2 – plasma steam reactor; 3 – steam generator; 4 – sequentially-connected power sources "Plasma-2"; 5 – compressor; 6 – cooling tower; 7 – Venturi scrubber; 8 – the system for the gas quenching; 9 – under-scrubber capacity; 10 – drip pan filter; 11 – fan (smoke exhauster); 12 – heat exchanger; 13 – soda solution tank; 14 – sludge tank; I – water supply; II – soda; III – synthesis gas; IV – for utilization

Smoke exhauster is an important element of the equipment. It provides gasification products extraction and creates a rarefaction in the reactor towards the atmosphere, in order to prevent any penetration of these products into the environment. Gasification products cleaning unit includes Venturi scrubber with gas quenching system and the capacity with the technological solution for scrubbing gasification products.

Table I presents the composition of the basic gasification products obtained from the medical waste in the equipment for plasma-steam gasification [6]. Gas composition has been determined by Agilent 6890 N gas chromatograph. In these experiments organic wastes of such average composition have been studied: 60 % of cellulose $C_6H_{10}O_5$ + 30 % of plastics based on polyethylene $(–CH_2–CH_2–)n$ + 10 % liquid (water). It is easy to show that the efficiency of the unit is quite sufficient for, at least, its energy self-provision, if to use such gas composition and the temperature at level of 1100…1400°C in the reactor, in the case of reciprocating power plants. We have also verified this fact experimentally. However, for hazardous wastes treatment, the environmental safety is the most important task.

The main physical result of this equipment experimental exploration was possibility of self-power supply by syngas with gas diesel electric station taking into account even low efficiency of electricity production ~30 %.

Table 1

Basic gasification products composition obtained from medical waste

Components	**H_2**	**CH_4**	**CO**	**CO_2**	**C_2H_4**
vol.%	49.89	1.99	35.25	2.52	3.37
Components	**C_2H_2**	**C_3H_6**	**H_2S**	**H_2O**	**Other**
vol.%	3.92	0.45	0.13	1.92	0.63

In general, previous experience of this facility proved the correctness of provided therein basic technical solutions. However, he also revealed some shortcomings of individual design solutions. They demand the revision process of further development. In particular this applies to the high-temperature thermal insulation of the reactor.

3. PLASMA GASIFICATION OF SEWAGE SLUDGE

During sewage treatment, the main pollutants are separated as sewage sludge. Its characteristics depend on the original pollution load of the water being treated, as well as the sludge treatment being carried out. The Kyiv wastewater treatment plant (known as Bortnychi station of aeration), which processes municipal and industrial sewage and run-off rain water, obtain 9000 m^3 wastewater over a twenty-four period. At present 9 million tones of sewage sludge are near this station.

The special problem of this waste is heavy metal in its compound [15]. The fact is that using of plasma technology, after the processing results in the minimum amount of solid residue, at the level of several percentages of its initial mass. Moreover, being fused to glass-like mass (vitrified), it is, in fact, a neutral substrate, safe for the environment. The temperature of the process vitrification is above 1700 K.

3.1. EXPERIMENT

Power of some plasma torches, used in industrial technologies is hundreds of kW, sometimes it even may reach the MW level [1]. Use of such plasma torches for laboratory research purposes causes significant difficulties because their maintenance is complicated. That is why relatively low-power steam plasma torch "Multiplaz 3500", which is on full-scale production has been used in this research [16] (Fig. 3). The maximum power of the plasma torch is 3.5 kW.

Quartz tube of inner diameter 3.2 cm and a length of 13 cm was used as a reactor. It placed a portion of sewage sludge to be studied in the process of gasification. Aggregate data on the composition of treated dry products of gasification are presented in Table 2.

With these data, it was determined formula response in terms of carbon, hydrogen, oxygen and organic matter

$$CH_{2.483}O_{0.530} + 1.334\ H_2O = 2.549\ H_2 +$$
$$+ 0.111\ CO + 0.876\ CO_2 + 0.013CH_4. \quad (2)$$

Fig. 3. Plasma torch system “Multiplaz 3500”

Gross formula of sewage sludge in this reaction correlates well with the results of [15] for their chemical composition.

Table 2

Basic gasification products composition obtained from sewage sludge

Components	H_2	CO	CO_2	CH_4
vol.%	71.8	3.1	24.7	0.4

3.2. THERMODYNAMICAL MODEL

In further consideration we have chosen a simpler gross formula of sewage sludge for fundamental thermodynamic estimates as $CH_{2,5}O_{0,5}$. Analysis of the process of plasma-steam gasification was made on a more optimal than (2) reactions [17]:

$$CH_{2.5}O_{0.5} + 0.5\ H_2O = CO + 1.75\ H_2 + Q_{TP}. \quad (3)$$

In fact, it is corresponds to technology of plasma-steam gasification (1), which was first implemented in Ukraine almost a decade ago (see [5]).

In order to optimize the plasma-steam gasification process of sewage sludge, there where analyzed also the next reactions [12, 13, 18]:

$$CH_{2.5}O_{0.5} + KH_2O + LO_2 \rightarrow CO + MH_2 + Q_{TP}, \quad (4)$$
$$CH_{2.5}O_{0.5} + KH_2O + LO_2 \rightarrow$$

$$\rightarrow CO + MH_2 + ECO_2 + DH_2O + Q_{TP}. \quad (5)$$

Reaction (4) as well as (3) is stoichiometric for obtaining products of gasification synthesis gas only. Nevertheless it has most wide functional possibilities to achieve the best indicators energy efficiency of the process as it allows varying the composition of the gasification agent.

Reaction (5) is nonstoichiometric one as there are the products of partial *combustion* of sewage sludge – CO_2 and H_2O – among the products of gasification. Generally speaking, we can write many variants of this reaction with different stoichiometric coefficients. Nevertheless actually only such of them are implemented in which the principle of maximum entropy is satisfied [19]. The software for thermodynamic calculations «TERRA» [20] was used to overcome this problem. In general, the problem was solved by methods of physical chemistry [19, 13, 18].

In reactions (3)-(5), $Q_{тр} = Q_R + \Delta Q$ is the total thermal energy, where one component Q_R is a result of chemical reactions in a mixture of a specified reaction and the other ΔQ is introduced into the reactor of gasifier by plasma torch jet such a way that reacting mixture has reached the desired temperature T_P to obtain quality products of gasification. For the reactions (3)-(5) the value T_P = 1250 K is accepted, as in this case in stoichiometric modes (3) and (4) only traces of CO_2, H_2O and CH_4 among the gasification products are founded.

Quantitative indicator of energy efficiency of the conversion process is the ratio

$$\eta = (P_{PL}^{C} + P_{O2})/ W_{SG}, \quad (6)$$

where $P_{PL}^{C} = \Delta Q/0{,}8$ – electricity consumption for production the plasma jet by efficiency of ~ 0.8 and for oxygen P_{O2}. W_{SG} – heat energy of synthesis gas from 1 kg of the original raw mixture.

In stoichiometric mode, the energy consumption of gasification process is the order of value of electrical power $\eta_{EE}W_{SG}$ that produced from synthesis gas by diesel power station of efficiency η_{EE}. This is important for mobile equipment as practically eliminated necessity to use additional sources of energy. In the mode additional oxygen input in gasification process, the consumption of synthesis gas for own needs of equipment $\eta_{EE}W_{СГ}/k_{HC}$ is about 30 %, where the coefficient of nonstochiometry of the production of synthesis gas k_{HC} is introduced. The rest can be used for the production of electricity to external consumers that will promote commercialization of development. Thus, in the proposed variant the processing technology correspond to the general idea of numerous publications in the world literature, known as the Waste to Energy.

Further improve the efficiency of this technology can facilitate the transition to more efficient methods of electricity production from obtained synthesis gas. This will lead to increasing value η_{EE} and, respectively, further decrease of the part of synthesis gas that is used for energy self-sufficiency of gasification equipment. Such prospects are associated primarily with fuel cell technology that has significantly greater efficiency than gas-diesel power stations.

These calculated data become the basis of the project "The development of steam-plasma technology of aeration stations sewage sludge conversion" offered by the competition of government of Ukraine; according to the results it obtained the status of a state order [21].

3.3. ASSUMPTION OF EQUILIBRIUM

Application of thermodynamic model requires proof equilibrium conditions in the object to be studied. In the case of hazardous waste processing in accordance with the requirements of Directive 2000/76/EC [14], problem is simplified by the presence of high-temperature zone, wherein gasification products staying a long time [18]. Taking into account also stage of gas particles ionization in a plasma torch and their cooling in the jet, the temperature profile has the general form represented in logarithmic scale in Fig. 4. Previously, we evaluated the conditions of formation in these conditions NO and NO_2, having the greatest specific times of formation and decomposition [9, 11]. As where shown, only NO has non-equilibrium concentration on leaving the reactor and NO_2 is in equilibrium in relation to NO.

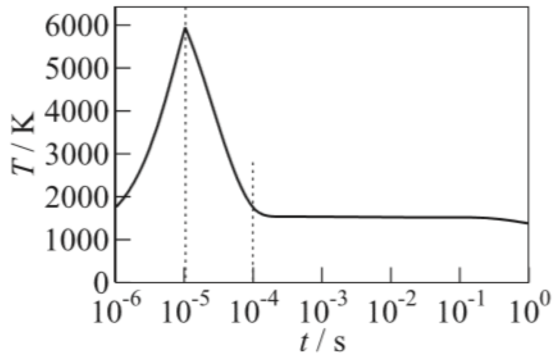

Fig. 4. Typical translational temperature profile for the plasma torch and gasifier reactor

4. NO_X FORMATION: KINETIC MODEL

The temperatures in plasma torch are favorable in terms of nitric oxides formation (see Figs. 4, 5). That is why, it is vital to rigorously predict production of NO_x in facilities using plasma torch and to apply special technologies in order to diminish it. The current part is aimed at kinetic modelling study of NO and NO_2 formation in a plasma torch and in the post discharge flow of model plasma gasifier.

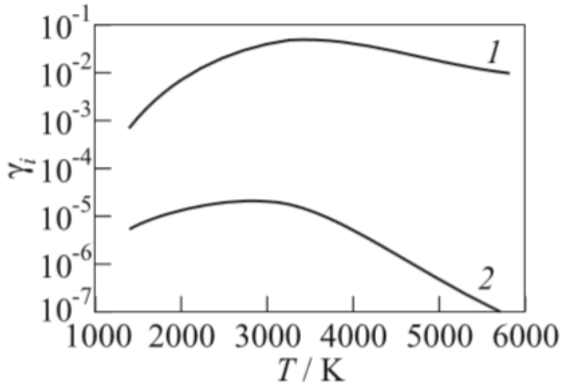

Fig. 5. Equilibrium values of NO (1) and NO_2 (2) mole fractions in dry air as a function of temperature

For simulation, three zones of plasma torch and reactor was used [22]. In the first zone, gas is heated in an arc discharge to the arc temperature T_{PL}. The second and third zones are plasma jet and reactor (see Fig. 4).

The thermally nonequilibrium kinetic model was used for the simulations of NO and NO_2 formation in a plasma torch and in the post discharge flow. It includes chemical reactions with neutral and charged particles, the processes of intermode vibrational-vibrational (V-V′) exchange, vibrational-translational (V-T) relaxation, electronic-electronic (E-E) exchange, electronic-translational (E-T) relaxation, excitation of vibrational and electronic states of molecules, dissociation, and ionization due to electron impact as well as reactions of associative ionization, electron attachment, and formation of electrons via ion-molecule reactions developed previously for dry air [23]. This model could be extended also in order to take into account plasma chemical reactions with H-containing species.

The example of the results obtained is presented in Fig. 6. As may be seen, outlet NO_x concentrations can be managed by varying the plasma torch parameters, in particular, the temperature of the arc.

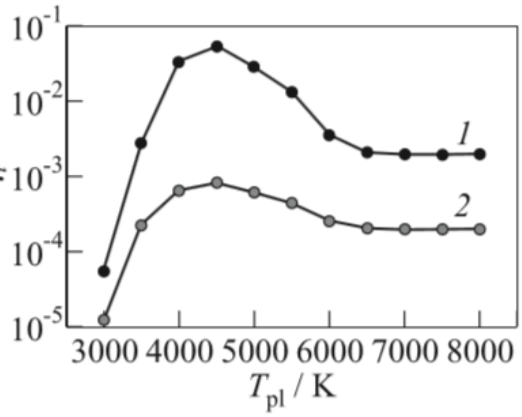

Fig. 6. Mole fractions of NO (1) and NO_2 (2) at the outlet of the reactor vs. discharge temperature T_{PL}

CONCLUSIONS

The most general assessments of ecological benefits and energy efficiency of plasma-steam gasification technologies are presented.

It is shown based on the thermodynamic and kinetic studies, that processing of sewage sludge using plasma technologies can be commercially attractive.

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ПОДДЕРЖИВАЕМЫЕ ПЛАЗМОЙ ПРОЦЕССЫ «ОТХОДЫ – В ЭНЕРГИЮ»

В.А. Жовтянский, Э.П. Колесникова, М.В. Якимович

Обсуждаются вопросы экологической безопасности и энергетической эффективности процессов производства альтернативного газового топлива на основе преобразования отходов биомассы с использованием пароплазменной технологии. Кратко описана пароплазменная установка для переработки отходов, исключающая риск образования диоксинов и фуранов в процессе газификации. Обсуждаются проблемы минимизации выбросов оксидов азота, а также исключения попадания в окружающую среду тяжёлых металлов. Показано, что предлагаемый вариант технологии переработки отходов соответствует общей идее многочисленных публикаций в мировой научной литературе, известной как «производство энергии из отходов».

ПІДТРИМУВАНІ ПЛАЗМОЮ ПРОЦЕСИ «ВІДХОДИ – В ЕНЕРГІЮ»

В.А. Жовтянський, Е.П. Колеснікова, М.В. Якимович

Обговорюються питання екологічної безпеки та енергетичної ефективності процесів виробництва альтернативного газового палива на основі перетворення відходів біомаси з використанням пароплазмової технології. Коротко описана пароплазмова установка для переробки відходів, що виключає ризик утворення діоксинів і фуранів у процесі газифікації. Обговорюються проблеми мінімізації викидів оксидів азоту, а також унеможливлення потрапляння в навколишнє середовище важких металів. Показано, що пропонований варіант технології переробки відходів відповідає загальній ідеї численних публікацій у світовій науковій літературі, відомій як «виробництво енергії з відходів».