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TRANSFER PROCESSES IN LOW-TEMPERATURE PLASMA

PLASMA PROCESSING OF MODEL RESIDENTIAL SOLID WASTE

V. E. Messerle,[a,b] A. L. Mossé,[c] A. N. Nikonchuk,[c] A. B. Ustimenko,[d,e] and R. V. Baimuldin[d]

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The authors have tested the technology of processing of model residential solid waste. They have developed and created a pilot plasma unit based on a plasma chamber incinerator. The waste processing technology has been tested and prepared for commercialization.

Keywords: *plasma processing, plasma chamber incinerator, residential waste.*

The problem of processing and disposal of residential solid waste (RSW) of various origin, including medicobiological waste (MBW), remains quite relevant. In recent years, scientific and technical literature has carried a great number of publications on the use of plasma energy sources (electric-arc plasma generators) in high-temperature installations for processing waste containing organic and inorganic substances (RSW, industrial and medical waste). The relevance of this area of focus is confirmed by the publication of a reference book on heat treatment of waste [1].

There are several options to implement a technology for high-temperature processing and treatment of RSW and of industrial and medical waste using plasma energy sources [1]:

1) plasmachemical elimination of supertoxicants at high temperatures directly in a plasma medium;
2) attacking the toxic-waste layer with a plasma jet or a plasma flow formed in a multijet mixing chamber;
3) waste heat treatment in a dense filtered layer using plasma energy sources;
4) afterburning of gases exhausted from incinerators using plasma energy sources.

It has been shown in [2] that in processing MBW, the organic mass is mainly turned into a synthesis gas with a content of fuel components of 77.4–84.6%, and the mineral part does not contain carbon and is basically represented by calcium oxide (CaO). Calculated by the TERRA thermodynamic-calculation program, the carbon gasification rate in plasma processing of MBW reaches 100% already at a temperature of 1000–1250 K. Unit (specific) energy consumption for processing MBW increases as the temperature of the process rises. At the temperature of processing MBW T = 1200–1600 K, the unit energy consumption varies with in the range 0.7–1.3 (kWh)/kg. Furthermore, the minimum energy consumption corresponds to the maximum share of air in the system, which is due to compensation for the endothermic effect of processing with heat release due to the reaction of carbon oxidation.

Experimental investigations were carried out with model RSW having the following chemical composition: C (34.15 wt.%), H (5.85 wt.%), O (6.29 wt.%), N (8.16 wt.%), S (0.94 wt.%), Cl (5.3 wt.%), H_2O (32.3 wt.%), Fe_2O_3 (3.0 wt.%), SiO_2 (2.0 wt.%), and $CaCO_3$ (2.0 wt.%) in a plasma chamber incinerator 0.33-m high, 0.22-m long, and 0.22-m wide with a lining 0.04 m thick [2]. This device is batch-operated and heated with a type PL-03/30 electric-arc plasmatron whose power supply requires an electric power of up to 35 kW [2–6]. The processing unit includes, apart from the plasma chamber incinerator, plasmatron power supply and starting systems and plasmatron and furnace combustion chamber gas and

[a]Institute of Combustion Problems, 172 Bogenbai Batyr Str., Almaty, 050012, Republic of Kazakhstan; [b]S. S. Kutateladze Institute of Thermophysics, Siberian Branch of the Russian Academy of Sciences, 1 Akad. Lavrentiev Ave., Novosibirsk, 630090, Russia; [c]A. V. Luikov Heat and Mass Transfer Institute, National Academy of Sciences of Belarus, 15 P. Brovka Str., Minsk, 220072, Belarus; email: mosse@itmo.by; [d]Scientific-Research Institute of Experimental and Theoretical Physics, 71 Al'-Farabi Ave., Almaty, 050040, Republic of Kazakhstan; [e]Scientific and Technical Organization "Plazmotekhnika," 22 Zverev Str., Almaty, 050010, Republic of Kazakhstan; email: ust@physics.kz. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 90, No. 5, pp. 1254–1259, September–October, 2017. Original article submitted August 31, 2016.

water supply systems. The unit is equipped with a system to sample gaseous products of the process for their subsequent analysis.

The plasma chamber incinerator is designed for plasmachemical processing of toxic MBW from medical and pharmaceutical enterprises. The mass of the waste batch loading varied from 5 to 7 kg, depending on its composition. The time of a complete waste-processing cycle, with account taken of the time of the incinerator′s cooling, was about 30 min. Packed in bags or boxes, with a mass of 5 to 7 kg, the waste was placed in the incinerator chamber, after which the loading hatch was shut. After starting the plasmatron, under the action of the air plasma torch, a mass-mean temperature of 1800 K was achieved in the chamber, the organic part of the waste material was gasified, and the inorganic part of the waste melted. The obtained synthesis gas was continuously taken out of the unit through treatment and cooling systems. The melted mineral part of the waste was removed from the furnace after its stoppage. Because of lack of oxygen in the plasma-supporting gas (air) in the furnace combustion chamber, there was only gasification of the waste. According to the process flow diagram, the resulting gas mixture moved from the combustion chamber to the afterburner chamber whereto air was additionally supplied for complete oxidation of exhaust gases. To increase the residence time of the gas mixture in the afterburner chamber at high temperature, this chamber was made in the form of a cyclone furnace considering that it is necessary to expose the gas to a temperature of 1500 K for 2 s [7] for complete decomposition of dioxins. On the inside, the chamber was lined with refractory material to sustain high temperature. The consumption of air supplied into the afterburner chamber was 0.2 kg/s.

Based on the results of experimental investigations, we determined the operating regimes of the plasma chamber incinerator, made an analysis of exhaust gases, obtained samples of condensation products taken from the combustion chamber, and identified their chemical composition. The gas at exit from the plasma incinerator has the following composition: 73.4 vol.% CO, 6.2 vol.% H_2, 29.6 vol.% N_2, and 0.8 vol.% S. The total concentration of synthesis gas ($CO + H_2$) amounted to 69.6%, which agrees well with calculation data. According to calculation, the synthesis-gas yield at a temperature of 1800 K amounts to 64.9%. The disagreement between the experiment and the calculation did not exceed 6.8%. As a result of an x-ray microspectrum analysis of the products obtained in the experiments, we identified the following content of elements collected in the furnace combustion chamber: Ca (54.6 wt.%), P (12.9 wt.%), and O (32 wt.%). These elements are present in the products in the form of oxides CaO (76.4 wt.%) and P_2O_3 (22.9 wt.%). The investigated sample also had traces of Al, Si, and K; its carbon content was 2.9 wt.%. An analysis of the condensed products collected on the filter after the exit from the furnace combustion chamber showed the presence in them of the following elements: Ca (41.5 wt.%), P (14.1 wt.%), O (33 wt.%), Si (0.5 wt.%), K (1.5 wt.%), S (1.1 wt.%), and Fe (1.7 wt.%). All the elements were present in the sample in the form of oxides CaO (67 wt.%), P_2O_3 (25 wt.%), SiO_2 (1 wt.%), K_2O (1.6 wt.%), SO_2 (1 wt.%), and Fe_2O_3 (2.5 wt.%). These results for the most stable nonvolatile component in the condensed phase (CaO) correlate with the calculation data: 71.61 wt.% of CaO. The disagreement between the experiment and the calculation did not exceed 7%, in terms of CaO concentration. The unit energy consumption in the process of processing MBW in the plasma chamber incinerator, based on experimental results, varied from 3.5 to 4.6 (kW·h)/kg.

Thermodynamic calculations performed for plasma gasification of RSW showed [8] that the maximum yield of fuel gas is reached at a temperature of 1600 K. In air-plasma gasification of RSW, it is possible to obtain a high calorific synthesis gas with a yield of 82.4% (31.7% CO and 50.7% H_2), and in vapor-plasma gasification, with a yield of 94.55 (33.6% CO and 60.9% H_2). The specific heat of combustion of the fuel gas obtained in air gasification was 3280 kcal/kg, and in vapor gasification, 3530 kcal/kg. At the optimum temperature, the unit energy consumption for air gasification of RSW was 1.92 (kWh)/kg, and for vapor gasification, 2.44 (kWh)/kg.

In accordance with the program of joint research of the Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus and the Scientific-Research Institute of Experimental and Theoretical Physics, experimental investigations of plasma processing of RSW were also conducted on a test bench of the Scientific and Technical Organization "Plazmotekhnika," whose main elements include a high-durability direct-current plasmatron with a nominal rated power of 70 kW and a batch reactor with a RSW productive capacity of 30 kg/h [8, 9]. The experimental setup (Fig. 1) includes, apart from a reactor with a plasmatron, plasmatron power supply and control systems, gas and water systems for the reactor with a plasmatron, and an exhaust-gas cleaning system. The setup is equipped with a system to sample gaseous and condensed products resulting from the process of gasification of organic waste for their analysis. The batch reactor installed at the test bench of the Scientific and Technical Organization "Plazmotekhnika" is shown in Fig. 2. The investigations were carried out using electric-arc plasmatrons of various types with a nominal rated power of 30 to 200 kW. The reactors' productive capacity for RSW varied from 3 to 100 kg/h. The electric output and productive capacity of the plasma reactor for RSW at the test bench of the Scientific and Technical Organization "Plazmotekhnika" exceeded the working parameters of the furnace

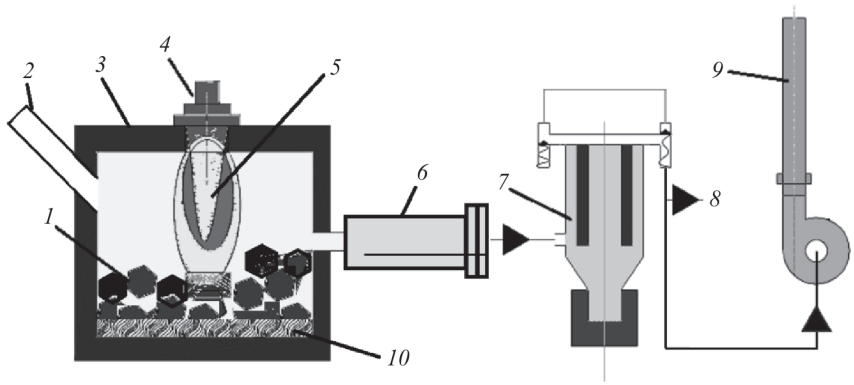

Fig. 1. Diagram of the experimental setup for plasma processing of RSW: 1) RSW gasification zone; 2) branch pipe for RSW feeding; 3) reactor; 4) electric-arc plasmatron; 5) plasma torch; 6) unit for cooling exhaust gases; 7) gas-cleaning unit with a bag filter; 8) system for sampling gas for analysis; 9) exhaust ventilation system; 10) slag-making zone.

Fig. 2. Experimental setup for RSW plasma processing on the test bench of the Scientific and Technical Organization "Plazmotekhnika."

at the test bench of the Heat and Mass Transfer Institute five to seven times, which is an important step for scaling working parameters of a plasma unit.

We conducted several series of experiments, using plasmatrons of various types: a Vortex-200 plasmatron, a high-durability plasmatron, and a PL-01/30 plasmatron. The Vortex-200 plasmatron used for processing plastic material, wood chip board (WCB), and cotton waste had working parameters I = 250 A, U = 350 V, P = 87.5 kW, and G_g = 700 L/min. The high-durability plasmatron used to process plastic material and glass had working parameters I = 240 A, U = 300 V, N = 72.0 kW, and G_g = 200 L/min at a temperature of 570 K at exit from the furnace. Figure 3 shows the torch from the high-durability plasmatron operating at a capacity of 72 kW. The torch temperature on the section of the cover was 5000 K. The PL-01/30 plasmatron used for processing plastic material had the working parameters I = 100 A, U = 300 V, N = 30.0 kW, and G_g = 100 L/min. The time of processing RSW in each experiment was 15 min. The average composition of the gaseous products of processing model waste using the PL-01/30 plasmatron in given in Table 1.

The plasma reactor at the test bench of the Scientific and Technical Organization "Plazmotekhnika" is designed to process RSW, including toxic MBW. The reactor is a cube lined with refractory bricks 0.065-m thick, with the size of its inner side being 0.45 m. The reaction volume of the reactor chamber is 0.091 m^3. There is a sight-hole in the reactor wall to

Fig. 3. Plasma torch from the high-durability plasmatron.

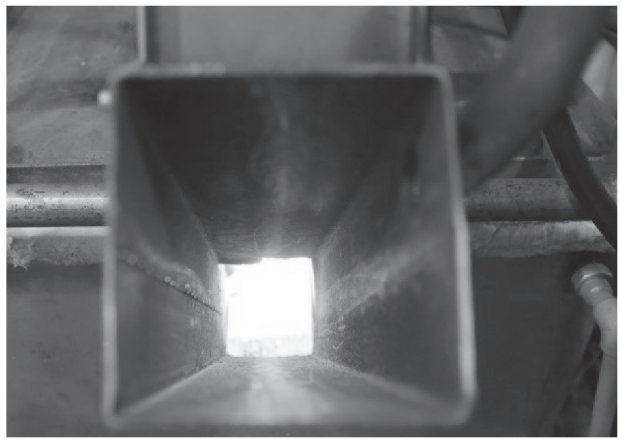

Fig. 4. Operating reactor with an open loading hatch.

TABLE 1. Composition of the Gas Arriving at the Afterburner Chamber

Components of the gas	Content of the components, vol.%
Carbon monoxide	63.4
Hydrogen	6.2
Sulfur	0.8
Nitrogen, chlorine, and other gases	29.6

measure temperature with a pyrometer in the reactor volume. The process of plasma gasification of organic waste was carried out in the following way. After starting plasmatron 4 and preheating reactor 3 to a temperature of the inner surface of the lining of 1100 K measured at a distance of 0.2 m from the reactor cover, briquetted RSW was fed to the gasification zone 1 through a branch pipe 2. The mass of each briquet was 0.4 kg. The RSW was gasified in an air plasma torch 5 that ensured a mass-mean temperature of up to 1600 K in the reactor volume. The resulting gaseous products were taken out of the reactor into the exhaust-gas cooling system 6, and the condensed products built up in the slag-making zone 10. The alignment of the zones of heat release from the torch 5, gasification of RSW 1, and slag-making 10 contributed to the intensification of the process of processing organic waste. The cooled gaseous products arrived at the gas-cleaning unit 7, after which the gas was fed to a gas analyzer using the sampling system 8. The exhaust ventilation system 9 ensured a pressure drop in the reactor down to 10 mm H_2O. Experiments showed that the time of a complete RSW-processing cycle is 30 min. Figure 4 shows the RSW-processing zone in a working plasma reactor.

Let us consider the operation of the reactor equipped with a high-durability plasmatron. Plasma-supporting air with a flow rate of 15 kg/h was used as a gasifying agent. The plasmatron's capacity was 72 kW (240 A and 300 V). After preheating the reactor for 15 min through the branch pipe 2 (Fig. 1), 20 briquets of model RSW with a total mass of 8 kg were successively charged into it. Under the influence of the air plasma torch, the mass-mean temperature in the chamber reached 1600 K, the RSW organic part was gasified, and the inorganic part melted and built up in the reactor′s slag-making zone. The obtained fuel gas was continuously taken out of the unit through cooling and purification systems. The melted mineral part of the waste was removed from the reactor after the completion of a working cycle.

Based on the results of experimental investigations of plasma processing model RSW, we determined the working regime of the plasmatron reactor, made an analysis of exhaust gases, obtained samples of condensed products sampled in the reactor′s slag-making zone, and indentified the residual carbon content in slag. Based on the results of a gas analysis made on an SRI 8610C gas chromotographer, the following gas composition was obtained at exit from the gas-cleaning unit: 26.5 vol.% CO, 44.6 vol.% H_2, and 28.0 vol.% N_2. The total concentration of the synthesis gas amounted to 71.1%, which

agrees well with thermodynamic-calculation data. As per calculation, the yield of synthesis gas at a temperature of 1600 K amounts to 82.4%: 31.7% CO and 50.7% H_2. Thus, the disagreement between the experiment and the calculation, in terms of the yield of the target product (synthesis gas), does not exceed 16%. As a result of an x-ray phase analysis made on a DRON-3 unit, the following slag composition was obtained: 63.0 wt.% Fe_3C, 21.0 wt.% $CaSiO_3$, 13.0 wt.% SiO_2, and 3.0 wt.% Fe. The carbon content in a slag sample determined by an absorption-and-weight method, amounted to 2.8 wt.%, which corresponds to a degree of gasification of carbon of organic waste of 91.8%. The disagreement between the experimental and calculated values of the degree of carbon gasification does not exceed 9%. No impurities were identified in the condensed products of RSW plasma gasification. Cleaning of fuel gas from chlorine-containing compounds should be conducted on carbon filters and biofilters.

Based on the experimental results, the unit energy consumption for RSW gasification in a plasma reactor was 4.5 (kWh)/kg (2.3 (kWh)/kg of working medium). In the calculations, the energy consumption for air-plasma gasification of RSW was 1.92 (kWh)/kg of working medium. This disagreement between the calculated and experimental values of unit energy consumption for the process is due to the fact that in thermodynamic calculations we determine the minimum possible energy consumption in an isolated thermodynamic system with no account taken of the heat and work exchange with the environment. In actual practice, both the plasma reactor itself and the plasmatron are characterized by the heat loss to the environment with a cooling water. Furthermore, the experimentally obtained values of unit energy consumption account for the energy consumption for preheating the reactor before feeding RSW. In the second and subsequent RSW processing cycles, there will be no additional energy consumption for preheating the reactor. In this case the disagreement between the experimental and calculated values of unit energy consumption for plasma gasification of RSW will decrease noticeably.

The results of modeling and experimental investigations of the process of plasma processing of RSW made it possible to formulate process recommendations for designing a pilot plasma unit and its practical use. The body of implemented investigations confirmed that plasma processing of RSW is characterized by the complete decomposition of any toxic substances. The main distinctive feature and advantage of the plasma technology is significant intensification of the process of waste destruction due to a more efficient transfer of energy to the processed materials. A significant feature of the plasma technology is the absence of high-molecular-weight compounds in the products of RSW processing. Plasma technology for processing RSW is multiphase, since it can be used to dispose of any waste irrespective of its qualitative composition. The developed plasma technology for processing RSW has been prepared for commercialization in consultation and coordination with specialized enterprises of Belarus, Kazakhstan, and Russia. It should be noted that it is possible to implement a mobile version of the plasma unit designed to service health facilities and pharmaceutical manufacturers. It is planned to conduct investigations of a plasma unit whose capacity and efficiency is approximately an order of magnitude greater than the capacity and efficiency of a plasma chamber incinerator, and to convert it into a mode of continuous feeding of briquetted RSW.

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NOTATION

G_g, flow rate of the plasma-supporting gas, L/min; I, current strength, A; P, power, kW; U, voltage, V.

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