Al-Farouk journal of sciences
Volume (2), Issue (4) (Spt, 2026)
ISSN: 3135-2359

مجلة الفاروق للعلوم
المجلد (2) العدد 4 سبتمبر 2026
ردمد: 3135-2359

PROCESSING AND DISPOSAL TECHNOLOGY OF TECHNOGENIC WASTE

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Received: 08/9/2026 Revised: 13/9/2026 Accepted: 05/10/2026 Publication: 05/11/2026

Abstract. The Article describes a technology designed for high-temperature processing and disposal of carbon-containing technogenic hazardous waste, where a steam-water plasmatron will be used as the main technological element. It is given the electrical substitution scheme of the reactor gasification zone. Demonstration calculation of thermal energy balance of the installation with conventionally selected geometrical parameters and initial compositions of waste and slag is presented.

Keywords: plasmatron; heat balance; water steam plasma; synthesis gas; technogenic waste.

Introduction

Technogenic wastes, such as municipal solid waste (MSW), which is one of the types of carbon-containing raw materials, are currently used to produce alternative gas fuels. The growth of world prices for hydrocarbons has led to interest in increasing the energy utilisation of MSW by producing electricity and heat. It is taken into account that the caloric value of 1 tonne of MSW is slightly higher than the caloric value of 1 barrel of oil [1].

The modern methods of waste utilisation and neutralisation are based on high-tech processes of their gasification to produce synthesis gas or on two-stage combustion using steam, gas, combined-cycle turbines or gas piston engines to produce electricity. At the same time, the second high-temperature stage guarantees complete neutralisation of the refined products from the formation of dioxins and furans. Emissions from modern MSW incineration power plants are several times less in volume and harmfulness than emissions from coal-fired power plants [1].
The advantages of this technology include:

a) absence of ballast nitrogen in gasification products which increases their calorific value in comparison with air gasification technologies, and proximity of elemental composition of synthesis gas (in terms of hydrogen content) to the composition of liquid hydrocarbons;
b) provision of high parameters of the gasification process (t = 1200 °C and higher) irrespective of the feedstock quality;
c) guaranteed neutralisation of gasification products of hazardous waste (for residence time at t = 1200 °C not less than 0.4 s).

The disadvantage, compared to other options of synthesis gas production, is its energy consumption. However, calculations show that this process becomes economically favourable for final production.

The mentioned advantages of plasma technologies make them practically alternative for destruction of products of toxic and hazardous technologies.

Purpose

Description of the technology allowing to realise environmentally safe processing of technogenic waste with accompanying production of high-calorie synthesis gas, where water steam is used as a plasma-forming medium.

Research Methodology

Fig. 1 shows the scheme of a plasma electric furnace with a steam-water plasmatron, which is designed for high-temperature processing of technogenic waste. It does not impose strict requirements to the moisture content of feedstock in the process of preliminary preparation, morphological and chemical compositions, as well as the aggregate state. Waste 1 enters through the loading unit 11 into the refractory-lined furnace 10, where under the action of energy of plasmatron 12.2, the arcs on the graphite electrode 12.1 and ohmic heat of slag 21 are gasified and the produced synthesis gas enters the cleaning and quenching apparatus 14, 15 – vortex scrubber. The purified synthesis gas from the settling tank 6 is fed to the combustion chamber 18 by means of the blower 17. The combustion chamber is simultaneously supplied with the required amount of air 4 for combustion of synthesis gas. Synthesis gas is sampled to determine its chemical composition 20 before the combustion chamber. Slag 7 formed during plasma gasification is removed from the slag collector 13. Sludge 8 is removed periodically from the slag tank 16. The water pump supplies water from the sump tank to the cleaning and quenching apparatus.

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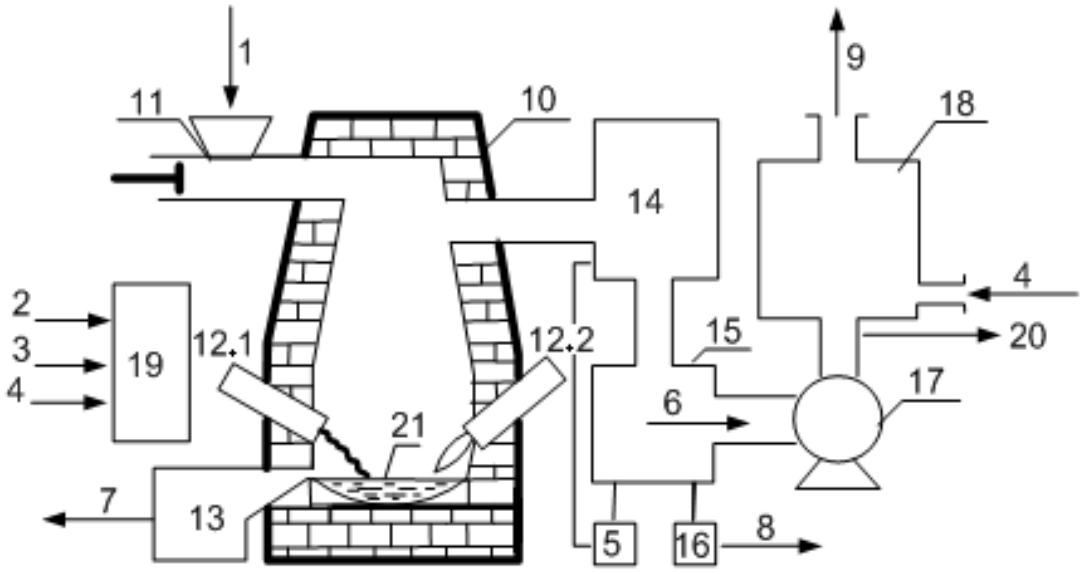


Figure 1 – Scheme of the plasma electric furnace

The sump tank contains a special heat exchanger for cooling water 15 coming from the vortex scrubber. The power supply system 19 provides supply of electric energy 2, plasma gas 3 and water 4 to the plasmatrons.

The combustion products of synthesis gas after the combustion chamber are partially sampled for chemical analysis. A discharge of 10...15 mm H_2O is maintained in the furnace volume.

The gas product obtained in the electro-technology consists of a mixture of carbon monoxide (≈40% CO) and hydrogen (≈50%) by 90-92%. Synthesis gas can be combusted to produce thermal energy in standard boilers or catalyst boiling bed apparatuses. However, the most promising is the use of mixture of CO and H_2 as the chemical feedstock. These technologies of synthesis gas utilisation provide low yield of domestic and industrial waste processing and increase the level of resource saving factor. The slag-metal mixture obtained as an additional product has inert properties when interacting with the environment and can be used for road construction, production of foamed granulate, slag wool, moulded products for a wide range of purposes. Properties and composition of the obtained slag can be changed by introducing additional fluxes in the form of SiO_2, CaO, etc. into the working space of the furnace.

The scheme of the plasma electric furnace in Figure 2.1 differs from the scheme of the plasma electric furnace given in [2] by the absence of the bottom electrode and the presence of the graphitised electrode 12.1.

The adopted electrotechnological scheme excludes the possibility of intensive formation of harmful compounds, including nitrogen oxides, due to the refusal to use air as an oxidising agent. According to theoretical calculations, this technical solution makes it possible to reduce the mass of obtained gases 2...3 times not only by excluding transport nitrogen, but also by separating in space and time the processes of complete carbon oxidation to obtain thermal energy. The proposed high-temperature electrotechnology may include devices for intensive quenching of the synthesis gas obtained with subsequent coarse and fine purification of gas streams from harmful components.

In the proposed technology, the gasifier reactor has a bath with liquid slag and metal at the bottom and a system for their removal in liquid form. Such a system is typical in metallurgy and has been known for a long time in the power industry, but in installations for destruction of hazardous waste it began to be used relatively recently and is being continuously improved [3].

The organic component of waste (including biological – toxic) and complex inorganic compounds are mainly decomposed due to the action of high temperatures, thermal radiation fluxes and the effect of active components appearing in the working space. The non-combustible component of the waste is partly transformed into dust and gas and removed from the working chamber together with the main flow of waste gases, and partly – passes into the slag bath. The liquid slag acts both as a solvent for the unreacted part of the waste and as a catalyst for some decomposition reactions. The metal component of the destroyed waste is partly burnt out and carried away with waste gases in the form, partly oxidised and transferred to slag, and large pieces mostly sink in the slag bath and melt at its bottom.

The condition that waste (e.g. medical waste) must be in a closed packaged form determines the periodic flow of packages for destruction. Accordingly, the operating regime of conventional incinerators cannot be quite uniform. The irregularity (diversity) of the composition of the waste in the packages adds to the unevenness of the operating regime. As a result, it may turn out that some small part of complex organic and inorganic substances, including biologically harmful (as well as part of simple combustible gases), will not have time to decompose and burn in the primary working chamber of the incinerator and will be carried away by the gas flow. This happens all the time in primitive incinerators operating without gas cleaning devices. An installation with a liquid metal bath at the bottom does not have this disadvantage.

The amount of solid residues generated during processing, e.g. medical waste, is about 20-25% [3]. 5-8% of this amount is carried away from the combustion chamber in the form of dust, up to 15-20% remains in the form of slag, and 2-3% - in the form of liquid metal at the bottom of the bath of the working chamber. Liquid slag from the bath in the working chamber of the plasma module

flows independently through an inclined pipe into an external slag collector: into a granulator tank or into water. The fine fraction is carried away to the hydraulic ash removal system. The coarse fraction of the granulate is removed periodically to the external accumulator.

The sludge – a complex mixture of oxides, salts and alkalis – after the crystalliser in the gas washing system can be recycled into individual substances or returned to the working chamber for remelting into slag.

The liquid metal from the bath bottom of the working chamber will be drained periodically through the bottom opening as it accumulates into a special caster of sufficient volume. The metal will be a very complex alloy, some of which may be used in metallurgical applications.

The first period of melting is melting of the metal charge. The graphitised electrode is lowered until it touches the charge, and the plasmatron is switched on in the indirect mode, when the arc burns between the anode and cathode of the plasmatron (Fig. 2). The outgoing plasma jet starts to melt the upper layers of the charge and heats up the graphite electrode.
After a certain time of operation of the plasmatron in the indirect mode, it is transferred to the direct mode, when the arc is closed to the charge being remelted, and the graphitised electrode starts to be lifted, forming a second arc discharge between it and the charge being remelted. The metal under the electrode and the plasmatron heats up, begins to melt and drips to the bottom of the bath. In the charge under the electrode and plasmatron are formed recesses, and then “wells” into which, as they are melted, the electrode and plasmatron are lowered. This process lasts until the electrode and plasmatron reach a puddle of molten metal on the bottom; then the charge of the walls of the wells begins to melt, the wells expand, the level of molten metal in the bath, and with it the electrode and plasmatron begin to rise until all the charge is melted [4].

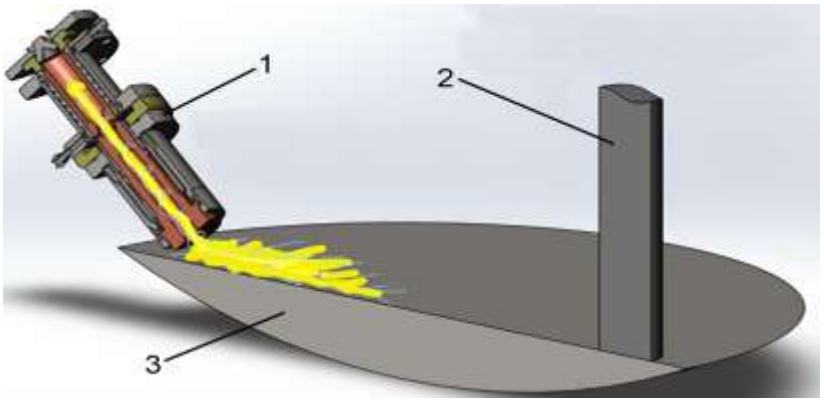


Figure 2 – Gasification zone of the reactor (in section):
1 – steam-water plasmatron; 2 – graphite electrode; 3 – charge material

This is a very hectic, unstable melting period, as the arc on the electrode surrounded by cold charge is very short and unstable, the walls of the wells under the arc are collapsing, falling on the electrode and the plasmatron, causing short circuits. At the same time, it is desirable to carry out the melting period as quickly as possible at maximum power, since the melting time determines the productivity of the entire plant and its efficiency factor. This period can be carried out at maximum voltage because the arcs are surrounded by cold metal protecting the lining of the walls and vault from their radiation (Fig. 3).

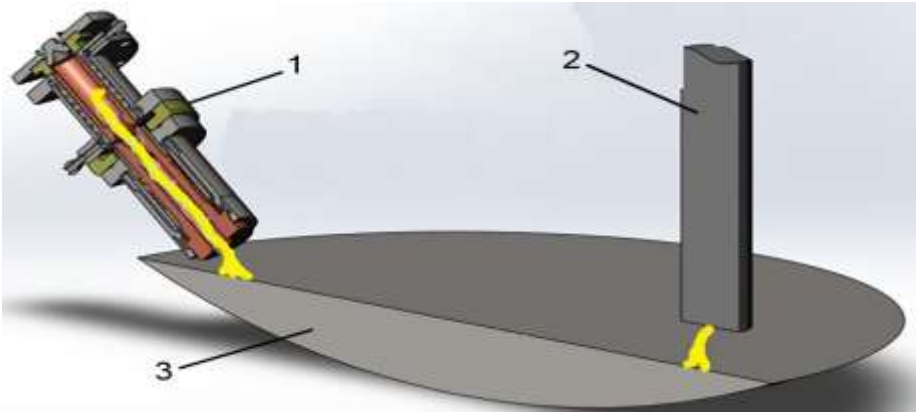


Figure 3 – Reactor gasification zone (in section):
1 – steam-water plasmatron; 2 – graphite electrode; 3 – melt

During the period when the metal is molten, the waste is loaded into the furnace, after which the gasification process starts immediately. The waste, as mentioned above, arrives in packaged form. At high temperature (about 1600 °C) in the gasifier chamber as a result of intensive decomposition of combustible components the following are formed: coke residue and gas containing mainly hydrogen and carbon monoxide (synthesis gas). The mineral part, consisting mainly of silicates and metals, melts and separates into metal and slag. The iron oxide in the slag reacts with the coke residue and is reduced to metal, forming carbon monoxide. The molten non-combustible inclusions continuously flow into the water bath to form pellets.

The recovered metal is continuously separated from the slag. The resulting melt consists mainly of iron, other metals and silicon. The composition of this mass and the amount of electricity required to produce it depend on the quantity and composition of the feed materials. The waste feed to the furnace must be regulated for the process to run properly. The slag cover must be constantly mixed with the incoming cold waste, which can be achieved, for example, by mixing the metal melt and slag.

Combustible gases produced by the reaction of oxygen with carbon rise upwards passing through the descending solid waste. Exhaust gas containing a significant amount of water vapour, some amount of “oil mist” and traces of harmful impurities enters the vortex scrubber (centrifugal-barbotage apparatus – CBA). The scheme and principle of operation of the CBA are described in detail in the work [2]. The gas obtained as a result of gasification is a pure combustible fuel. This gas has a great advantage over natural gas, as it does not contain sulphur compounds and nitrogen oxides.

During the period when the metal is fully molten, the walls of the gasifier are very hot, as the arcs are extended and radiate heat strongly onto the lining, which is heated to the temperature limit of the material, so the voltage must be regulated and reduced, or the waste must be continuously fed into the gasification chamber.

It follows from the above that it is necessary to be able to regulate the plant power and (voltage) within a wide range, and its electrical equipment must be able to withstand frequent short circuits and load impact.

Electricity consumption for the processing of technogenic waste depends not only on technological factors – elemental composition, ability of personnel to conduct the process, condition of the lining, quality of electrodes, amount of downtime, etc., but also to no lesser extent on how correctly selected the electrical mode of the furnace [4]. The mode can be adjusted, for example, by changing

the arc length on the graphitised electrode, and hence the total circuit current. This method makes it possible to regulate the furnace mode continuously and smoothly by raising and lowering the electrode by means of an automatic control system, maintaining the furnace current and power at the required level.

For convenient operation of the installation, it is advisable to identify the current dependence of its main parameters; useful to total (active) power, electrical losses, electrical efficiency and power factor. Such dependencies are built on the basis of the electrical substitution diagram of the installation; they are called electrical characteristics.

The electrical substitution diagram of the gasification zone can be represented as a single-phase chain of series-connected active resistances (Fig. 4). The active resistances of the circuit include: resistance of the plasmatron arc R_{d1}, resistance of the arc at the electrode R_{d2} and resistance of the bath melt R_m. Among this series of resistances R_{d1} and R_{d2} belong to non-constant resistances, because during operation the values of their resistances can change arbitrarily, and R_m can be attributed to the constant resistance, if composition and temperature of the slag are maintained at the given level.

Let's assume that there is a certain high-temperature plant designed for treatment and destruction of hazardous waste in which the developed steam-water plasmatron, graphite electrode and slag bath are the main structural elements. In such a case, it is strongly recommended that an energy balance be drawn up, which will give a clear energy picture of the whole process and will allow the identification of measures to improve the utilisation of such an installation and its flow rates.

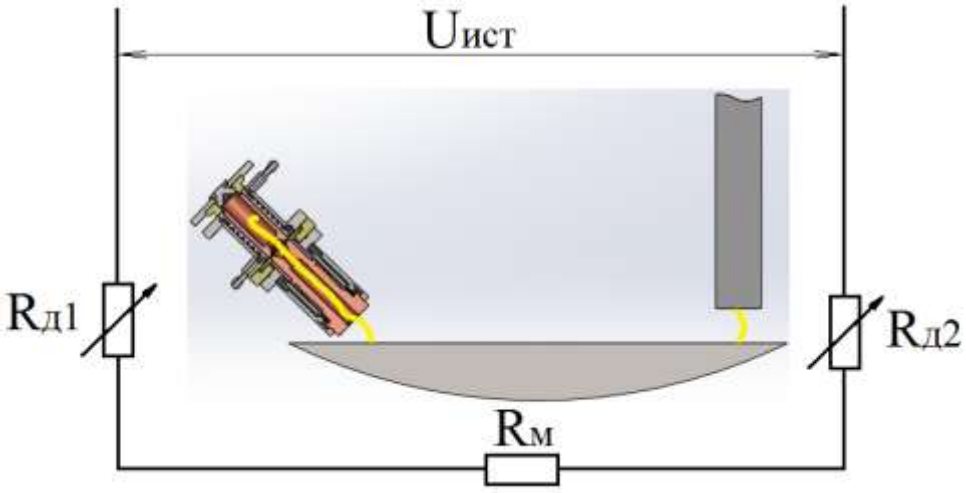


Figure 4 - Electrical substitution diagram

In this case, the input item of the energy balance will include the following components: Q_1 – heat brought into the installation with electric energy; Q_2 – heat brought into the furnace with waste (if they are preheated to a certain temperature); Q_3 – heat released in the reactor during exothermic reactions. The expenditure item of the energy balance will include: Q_4 – heat of smelting and gasification products – slag and waste; Q_5 – heat absorbed during endothermic reactions;
Q_6 – all kinds of heat and electric losses of the plant. As a result, the energy balance will look like this:

$$Q_1 + Q_2 + Q_3 = Q_4 + Q_5 + Q_6 \pm \Delta, \quad (1)$$

where Δ - tolerance due to assumptions and calculations.

Here is a demonstration calculation of the energy balance equation (1) for an electrical process installation, the geometric parameters of the bath with liquid slag which are shown in Figure 5.

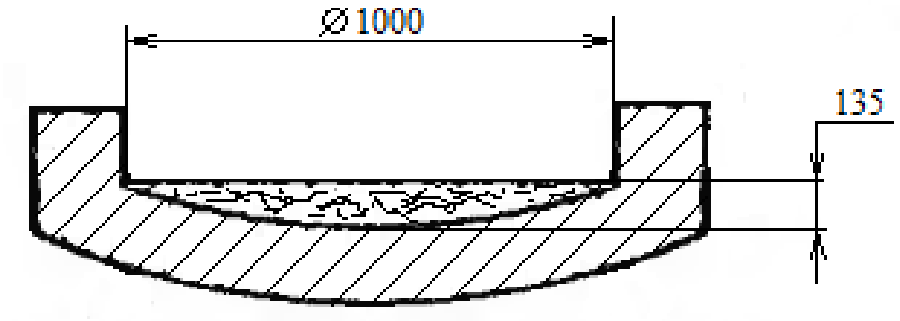


Figure 5 – Bath geometry (mm) for liquid slag

As initial data we take the following parameters:
1) mass of carbon-containing waste fed into the reactor chamber = 100 kg, elemental composition in the initial state (% of mass): C = 34,83; H = 4.42;
O = 23.57; N = 1.38; S = 0.13; Cl = 3.47; SiO_2 = 17.33; H_2O = 14.87.
2) amount of plasma-forming medium fed into the water steam gasification chamber = 10 kg.
3) mass of liquid slag ≈ 160 kg, elemental composition in the initial state (% of mass): SiO_2 = 10.4; MnO = 1; Fe = 2; CaO = 52.5; MgO = 4.5; Al_2O_3 = 5.

It should be noted that calculation of the energy balance is given for the first cycle of operation of the installation (the first loading of waste into the gasifier). This mode of operation is the most energy-consuming, as the mineral part of the whole mass has to be heated from 20 to 1600 °C. If the installation is operated continuously, then at subsequent cycles of waste loading into it, the form of the energy balance equation will differ from (1), since the slag will not have to be heated. It follows from the above that when designing the components of the installation, as a basis for the calculation should take this mode.

At first, it is necessary to calculate the amount of heat required to heat all organic and mineral parts of the mass, simultaneously loaded into the gasifier to a given temperature. Let's calculate the amount of heat required to heat 100 kg of medical waste. The general formula for determining the energy:

$$Q_{ob} = \sum_{i=1}^{n} Q_i \ , \tag{2}$$

i.e. the total amount of heat (energy) is determined by the sum of individual amounts of heat required to heat the respective material components:

$$Q_i = m_i C_{pi} \Delta T \ , \tag{3}$$

where m_i is the mass of the i component of the substance, Cp_i is the specific (average over the temperature range) heat capacity at constant pressure. From the reference book [5] we find the values of Cp on the temperature interval 20°C – 1200 °C for: $C - 14.23$ J/(mol·deg); $H_2 - 28,85$ J/(mol·deg); $O_2 - 31,69$ J/(mol·deg); $N_2 - 30,38$ J/(mol·deg); $S - 28$ J/(mol·deg); $H_2O - 36,77$ J/(mol·deg); $SiO_2 - 60,18$ J/(mol·deg).

We determine the amount of heat required to heat 100 kg of medical waste, kW·h:

$$H_2 - 4420\,\text{g} = 2210 \cdot 28{,}85 \cdot 1180 / 3600 = 20{,}9;$$

$$N_2 - 1380\,\text{g} = 49{,}3 \cdot 30{,}38 \cdot 1180 / 3600 = 0{,}5;$$

$$C - 34830\,\text{g} = 2902{,}5 \cdot 14{,}23 \cdot 1180 / 3600 = 13{,}5;$$

$$O_2 - 23570\,\text{g} = 736{,}6 \cdot 31{,}69 \cdot 1180 / 3600 = 7{,}7;$$

$$H_2O - 14870\,\text{g} = 826{,}1 \cdot 36{,}77 \cdot 1180 / 3600 = 9{,}9;$$

$$SiO_2 - 17330\,\text{g} = 288{,}9 \cdot 60{,}18 \cdot 1180 / 3600 = 5{,}7;$$

$$Q_{oth} = 20{,}9 + 0{,}5 + 13{,}5 + 7{,}7 + 9{,}9 + 5{,}7 = 58{,}2.$$

Taking specific energy consumption for steam production from Fig. 6 [6], let's determine the amount of heat required to heat 10 kg of water:

$$Q_B = q \cdot m = 3{,}5 \cdot 10^4 \text{ kJ} = 9{,}7 \text{ kW},$$

where q – specific energy consumption for obtaining dry steam, kJ/g; m – mass of plasma-forming medium - water.

Then, let us determine the amount of heat required to heat 160 kg of slag. Information about thermophysical properties, including heat capacity of refining slags, depending on their composition, is practically absent in the literature [7-9]. Thus, in the work [9] the results of studies of thermophysical real slags in the range of their basicity from 0.5 to 1.4 are given, which show that following increasing basicity, thermal diffusivity, heat capacity and thermal conductivity of slags decrease (Table 1).

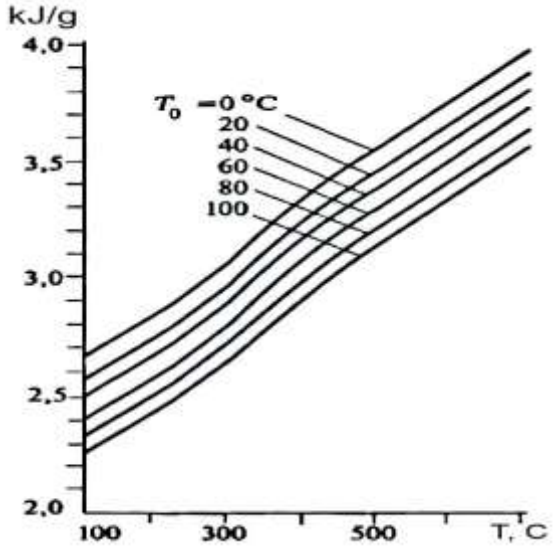


Figure 6 - Specific energy consumption to produce dry superheated steam

Table 1 – Heat capacity of slag

CaO/SiO_2	Temperature conductivity, α, $(m^2/c)10^{-6}$		Isobaric specific heat capacity, Cp, J/(kg·K)		Thermal conductivity, λ, W/(m·K)	
	1000 °C	1200 °C	1000 °C	1200 °C	1000 °C	1200 °C
0,55	1,22	1,19	1215	1440	3,4	3,9
0,8	1,05	0,99	1050	1270	2,6	3,0
1,37	0,88	0,85	1120	1320	2,3	2,6

To determine the required heat to heat 160 kg of slag, we use the averaged data from Table 1 and formula (3):

$$Q_{shl} = 160 \cdot 1{,}1 \cdot 1580 / 3600 = 77{,}2 \text{ kW}.$$

After we have determined the heat that must be spent to heat the waste, water and slag to a given temperature, let's determine the component Q^4, which is included in the equation of energy balance:

$$Q_4 = Q_{oth} + Q_B + Q_{shl} = 58{,}2 + 9{,}7 + 77{,}2 = 145{,}1 \text{ kW},$$

$$Q_3 - Q_5 = 4 \text{kW}.$$

For numerical simulation of electromagnetic processes in the metal melt, specialized software packages and multiphysics packages are now widely used [10-15]. Determination of the released heat in the bath with liquid slag has been carried out by numerical method in the ANSYS program package. Great difficulties in the use of application program packages arise with the choice of the solution method, settings, imposition of boundary and initial conditions, as well as in the choice of the computational domain and the dimensionality of the model.

The family of dependences of the electrical conductivity of slags on their basicity and temperature are presented in Fig. 7 [9]. Based on these data, the resistivity for our selected slag at a temperature of 1600 °C ≈ 0.018 Ω·m.

To construct the physical model, the following assumptions have been made:
1) the medium is assumed to be non-magnetic (μ = 1);
2) the medium is a good conductor and its dielectric constant can be neglected (ε = 1);
3) physical characteristics of the medium are assumed to be homogeneous and isotropic;
4) chemical reactions are not taken into account;
5) flowing processes are described in a stationary formulation.

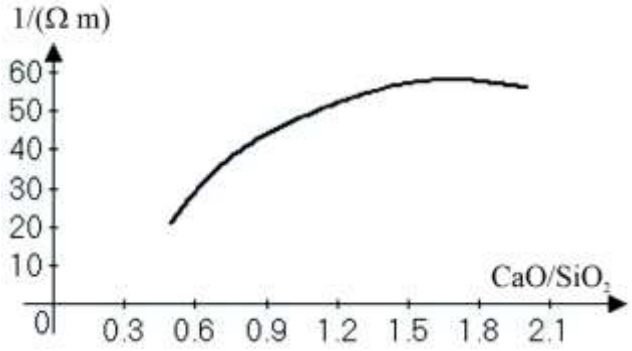


Figure 7 – Dependence of slag conductivity on basicity

Results of the study and their discussion

The problem has been solved under the following boundary conditions:

1) At the edges of the surface of the modelled melt volume, the arc roots have been conventionally selected, through which direct current flows in the range from 100 to 300 A (in Fig. 8, the current flow is indicated by arrows).

2) The fact that the magnetic flow is assumed not to extend beyond the model regions implies that the flow will be parallel to the outer boundaries of the model. This assumption is possible if the dimensions of the modelled air space surrounding the magnetic system are sufficient to solve the problem.

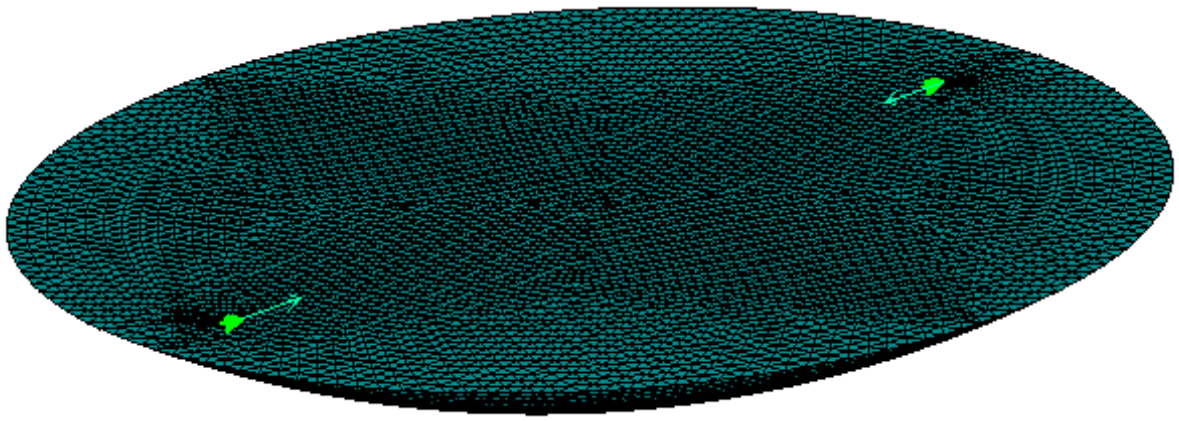


Figure 8 – Boundary condition of the flowing current

Following the numerical simulation, the dependence of the released heat in liquid slag (at specific electrical resistance of slag 0.018 Ω·m) on the value of the current flowing through it has been obtained (Fig. 9).

Figure 10 shows the dependence of the released heat in the melt on its specific electrical resistance and the value of the current flowing through it. The graphs show that if to provide regulation of specific electrical resistance of the melt in the operating mode in the range of 10-5... 10-4 Ω·m, the heat released in the bath melt will be 10...100 kW, respectively.

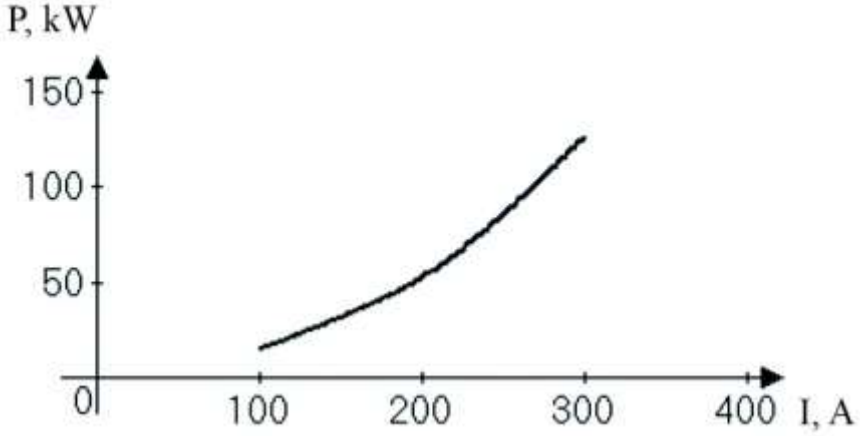


Figure 9 – Heat released in the slag, depending on the current flow

To determine the heat released in the arc discharge between the melt and the graphite electrode, it is necessary to experimentally obtain a family of CVC (current–voltage characteristic) of this arc discharge. Not having such data, we conditionally assume that the power released in this arc is equal to half of the power released in the arc of the plasmatron.

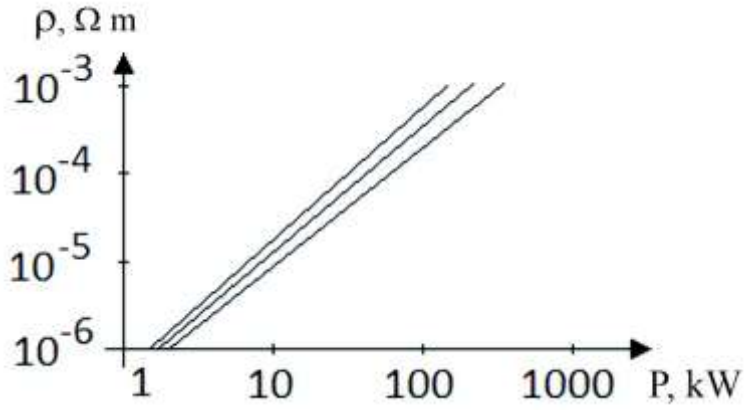


Figure 10 – Dependence of heat released in the melt on its specific electrical resistance

Such an assumption is made on the basis of obvious unequal importance of these arcs, because, firstly, the arc on the graphite electrode burns partly in steam-water medium and partly in synthesis gas and, secondly, its length is shorter than the length of the plasmatron arc, which leads to a lower power release compared to the plasmatron arc. At a current of 200 A, in the arc of the plasmatron will be released 70 kW [16], hence in the arc on the graphite electrode – 35 kW and in the bath with liquid slag – 55.5 kW (Fig. 9), consequently:

$$Q_1 = 70 + 35 + 55{,}5 = 160{,}5\,\text{kW}.$$

The heat Q_2 represents the heat content of products loaded into the units during the melting process. The value of this heat in the present case is small and may not be taken into account because the waste has not been previously heated. In other cases, Q_2 may constitute the main part of the incoming balance item.

It is known from practice that the gasifier reactor in most cases has an efficiency of 90%, consequently:

$$Q_6 = \left(Q_1 + Q_3 - Q_5\right) \cdot 0{,}1 = \left(160{,}5 + 4\right) \cdot 0{,}1 = 16{,}5 \text{ кВт.}$$

As a result, the energy balance equation will be as follows:

$$160{,}5 + 0 + 45{,}8 = 145{,}1 + 41{,}8 + 16{,}5,$$
$$206{,}3 \approx 203{,}4$$

The tolerance of energy calculation in this case is as follows $\Delta \approx 2\%$.

Conclusions

The plasma-arc technology of hazardous waste processing has a number of advantages in comparison with common methods of their neutralization, for example, as installations of fire neutralization of layer type: the process cycle is closed; the process is waste-free; all organic compounds are completely destroyed, pathogenic microflora is destroyed; synthesis gas, obtained as a result of gasification, contains less harmful impurities than gases of incinerators. The resource of the plasmatron operation increases: firstly, due to the additional heat released in the slag melt, due to which the load on the plasmatron can be reduced, and secondly, when the plasmatron is operated in the melting mode, the auxiliary electrode-cathode ceases to experience the thermal load from the arc root, which multiplies the resource of the plasmatron operation as a whole.

Also, the melted slag from the working chamber will be an inert building material of high quality, which is unattainable at low- and medium-temperature combustion of technogenic waste. Such slag can be used, first of all, for repair and construction of roads and sidewalks.

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