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Plasma reactor for material synthesis and waste recycling

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Abstract. At present, the cleanliness of the human environment and the improvement of the environmental performance of the technologies used by them are becoming increasingly important. In this regard, the problem of high-quality waste processing has arisen. Existing industrial methods for the destruction, neutralization and disposal of waste (landfills, sorting, earth filling, incineration, biothermal composting do not meet the requirements of environmental legislation. In this work, an atmospheric electric arc reactor was developed for waste disposal.
Keywords: plasma reactor, waste recycling.

1. Introduction

In the 21st century, population growth, consumerism and a linear approach to industrialization have led to a rapid increase in the generation of a variety of waste.

Waste can be divided into nine types: industrial or industrial waste, agricultural and forestry waste, municipal solid waste, mining waste, construction and demolition waste, medical waste, radioactive waste and universal waste [1]. Consequently, these wastes increase environmental pollution and raise concerns about the unsustainability of current economic growth patterns [2]. Traditional methods such as burial, incineration and composting are widely used to dispose of solid waste [3]. However, the consumption of a significant amount of energy, the release of carbon dioxide, the use of non-renewable natural resources as raw materials and the maximization of the value of waste motivated the use of waste as a raw material [4] for the production of polymers [5], building materials [6] and ceramics [7]. Among the main processed wastes, the following wastes are used: ash and slag waste, blast furnace slag, polished tile waste, red mud, cullet.

2. Experimental setup

In the course of the research, an atmospheric arc plasma reactor was created [8], a system for its automation was developed, and software was written for it [9]. The plasma reactor is a combined type reactor with a horizontal arrangement of electrodes. The design of the reactor with a horizontal arrangement of electrodes makes it possible to work with dielectric materials, which makes it possible for current to flow through the samples. Also, due to the design features of the reactor, it is possible to work with liquid materials; when using a vertical type reactor, there is a possibility of splashing of liquid materials and problems with the moment of initiation of an electric arc discharge when working with dielectric samples. The use of an atmospheric reactor with a horizontal arrangement of electrodes makes it possible to achieve the following advantages in high-temperature waste processing and material synthesis: no oxidation of the resulting product, ensuring the process of registering gases released during waste processing, which is due to the design of the installation, which will be described below.

The electric arc reactor consists of a DC power source made on the basis of a rectifier-inverter welding transformer of the Colt Condor 200 brand, such a source has an operating output current of 20–200 A and a supply voltage of 220 V. The materials to be processed are placed on the bottom of a working unsealed graphite chamber in the form of a glass (graphite crucible), which has two through holes in the walls, where the electrodes are inserted. In such a system, the electrodes, cathode and anode, are two rods made of high density graphite. The anode is fed into the reactor zone using a movable current-carrying holder, the cathode is fixed and located directly inside the graphite chamber. To analyze the gaseous medium in the reaction zone, during the waste processing process, the graphite cup is closed with a graphite lid, which has a through hole for installing the gas analysis path. The gases released during the processing of raw materials are pumped to the gas analyzer Boner Test-1.

The collection of the obtained materials is carried out from the bottom and walls of the graphite cup, however, the waste processing process is accompanied by combustion and, as mentioned earlier, the release of gases, which leads to the transfer of the synthesis product to the graphite cover.

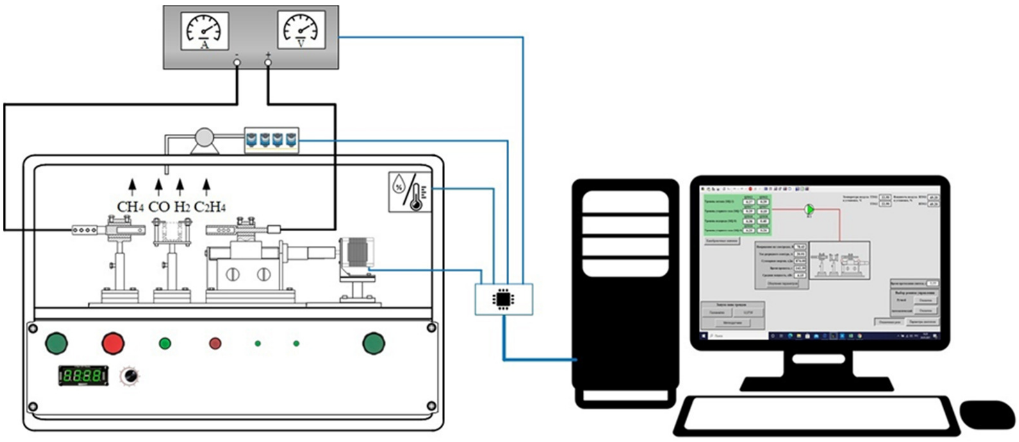


Fig.1. Schematic diagram of a direct current electric arc reactor.

The main parameters of the process of plasma processing of materials are current-voltage characteristics – the value of current and voltage. Registration of the current in the system occurs using a current sensor brand CSLA1DJ, based on the Hall effect. This type of sensors has a voltage output of 0–6 V, and the ability to detect currents up to 225 A. The voltage in the system is recorded using an ohmic voltage divider with an operating range of 0–120 V. A two-channel digital oscilloscope reads readings from a current sensor and a voltage divider in a digital form with the possibility of transferring data to a computer. To automatically collect current and voltage readings, as well as calculate energy indicators, software was developed [9], which makes it possible to transfer data to a personal computer. Fig.2a shows typical current-voltage characteristics and energy indicators of Fig.2b, obtained using the registration system.

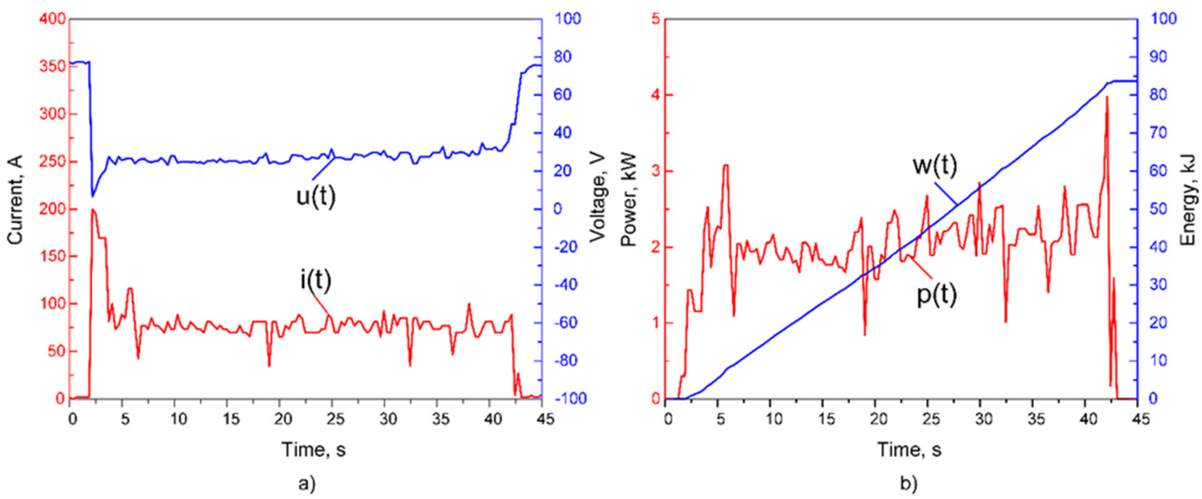


Fig.2. a) Typical oscillograms of current $i(t)$ and voltage $u(t)$; b) typical readings of power $w(t)$ and process energy p(i).

The oscillogram (Fig.2a) shows the stages characteristic of the process of synthesis and processing of materials: initiation, combustion, and extinction of the arc discharge. This is due to the principle of operation of the arc reactor: when the cathode and anode come into contact, a short circuit occurs in the system, after which the anode is slowly removed from the cathode, as a result of which a discharge gap is formed and an electric arc is initiated. Upon completion of the initiation of the discharge, the process of burning the arc follows, to complete the process of processing the material, the arc is broken by retracting the cathode to a distance at which the process of stable burning of the arc is impossible.

3. Results and discussion

The regulation of the process of processing and synthesis in the system is possible by changing the parameters of the current strength and the time of exposure to the sample. Table 1 presents the main parameters of the reactor operation and their influence on the mass balance of the system. Each experiment consists of a selection of at least 5 experiments carried out on a DC arc reactor.

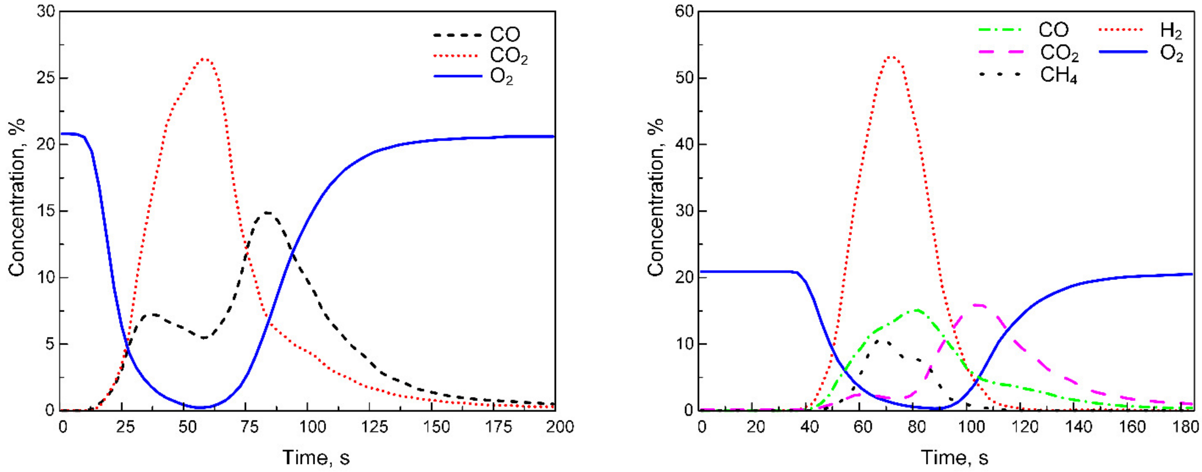
Table 1. Influence of operating parameters of an arc reactor on the mass balance of the system

№ exp.	*I*, A	Recycling time, s	Δ*m* cathode, g	Δ*m* anode, g	Δ*m* crucible, g	Δ*m* lid, g	Weight of raw materials, g	Obtained sample from the lid, g
1	50	30	0.017	-0.020	0.366	0.006	1.047	0.0024
2	75	30	0.089	-0.083	-0.011	-0.001	1.004	0.0107
3	100	30	0.121	-0.178	-0.055	-0.021	1.017	0.0116
4	125	30	0.129	-0.391	-0.163	0.139	1.053	0.0103

Under the data obtained from a series of experiments on the gasification of liquid hydrocarbons with current regulation, one can notice a change in the mass of the elements of the system, namely: the mass of the electrodes, the graphite cup (crucible) and the graphite cover. It should be noted that an increase in the current strength at the power source leads to an increase in the temperature in the reaction zone, hence all changes in the mass balance of the system elements follow. An increase in the current strength leads to an increase in the mass of the cathode due to the formation of a cathode deposit, in turn, the reverse process is observed with a change in the mass of the anode, crucible, and lid. The change in the masses of graphite electrodes can be associated with the principle of operation of direct current electric arc reactors. After the initiation of the arc discharge, mass transfer from the anode to the cathode occurs, resulting in the formation of graphite deposits on the cathode, which leads to an increase in the mass of the cathode, the same effect is found in the work of Joseph Berkmans [10]. However, in this case, not all the mass passes from one electrode to another; this can be due to the specifics of the experiment.

The non-vacuum electric arc method proceeds in an air atmosphere at high temperatures, but the treated samples do not undergo oxidation, which is associated with the effect of self-shielding of the reaction zone. The moment of initiation and subsequent combustion of an electric arc discharge is accompanied by high temperatures (more than 10.000°C at the place of discharge initiation [11]), which leads to the consumption of a graphite rod, part of which passes to the cathode, as described earlier, the remaining particles of graphite, in turn, are released into the air and, when interacting with oxygen (oxidation of carbon), form compounds of carbon dioxide (CO_2) and carbon monoxide (CO) gas, which leads to shielding of the reaction zone and prevents sample oxidation during synthesis; this effect was described in [12]. Also, the effect of self-shielding and the absence of oxygen in the reaction zone can be confirmed by data obtained from a flow gas analyzer (Fig.2a).

According to the data of gas analysis during the processing of liquid hydrocarbons (Fig.3b), one can also observe the process of carbon oxidation with the formation of CO and CO_2, in addition to the release of these gases, methane CH_4 and hydrogen H_2 are also released. During the processing of raw materials, a decrease in the mass of the crucible and lid is observed, which can be explained by the interaction of these elements with atmospheric air at high temperatures, which also leads to carbon emissions into the air and its oxidation, as a result of which the mass loss increases in proportion to the increase in current strength.



a) b)

Fig.3. Typical dependences of gas concentration on time: a) when the crucible is empty, b) when processing liquid hydrocarbons.

However, when the reactor operates at low currents (50 A), an increase in the mass of the crucible is observed, which is associated with the specifics of working with liquid hydrocarbons. According to the data from Table 1, it can be seen that the sample output practically does not change after 75 A, but in the 50 A mode, the output of the final product is 4 times less than other operating modes. The reason for the increase in the mass of the crucible can be associated with the incomplete completion of the process of processing liquid hydrocarbons. The operating mode of 50 A is accompanied by lower temperatures of the reactor, which does not allow complete processing of the original fuel, as a result, the remains of liquid hydrocarbons can condense on the walls of the graphite cup, which leads to an increase in the weight of the crucible.

A method for regulating the process by the time of exposure to the sample at direct current was also noted. It is worth noting here that when the time of exposure to the sample changes, the same processes occur as when the current strength changes: an increase in the mass of the cathode, a decrease in the masses of the anode, crucible, and lid. A shorter period of exposure to the sample may lead to incomplete processing of the feedstock, so the main task when starting research on waste processing is to determine the optimal mode of operation. The optimal operating mode of the reactor is the mode in which the initial sample is completely processed and the maximum yield of useful gases, namely hydrogen and methane, which decomposes into carbon and hydrogen at higher temperatures, occurs. After determining the optimal operating mode (75 A and 30 s), a series of experiments were carried out.

This method was also used to study the processing of glass waste to obtain a ceramic material based on silicon carbide [7]. Also, rubber products were processed to produce carbon and synthesis gas [13].

4. Conclusion

Atmospheric electric arc reactor was developed for waste disposal. This research shows the original atmospheric plasma facility and provides information about its testing. A feature of the applied processing method and the atmospheric electric arc reactor is the possibility of their implementation without the use of vacuum equipment. This is possible due to the effect of self-shielding of the reaction volume from atmospheric oxygen. This approach greatly simplifies the design of an electric arc reactor and its operation.

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