Mathematical modeling of plasma-thermal gasification of technogenic wastes

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Abstract. The electrical and thermal characteristics of a plasma-resistive furnace in the drying zone during the utilization of industrial waste have been investigated. The dependences of the power release in the drying zone for various electrical resistivity of the mixture were obtained. It is shown that the introduction of additional resistive heating in the drying zone reduces the load on the plasmatron, increasing the lifetime of the electrodes.

1. Introduction
Disposal of solid municipal waste is one of the most important problems in modern society. Modern waste disposal technologies are switching to the use of high temperature operating modes over 1500°C. Electroplasma installations meet the required technology parameters. But these installations consume a lot of energy (1 MW per 1 ton). High consumption of electrical energy is the main disadvantage of electroplasma installations today. To solve this drawback, it is necessary to develop new approaches to electroplasma technologies for waste processing. The creation of a combined nargev is a new technical solution to reduce energy consumption by electroplasma installations. Plasma resistance heating is a new combination heating. Resistive heating provides additional energy release in the drying zone of the heat treatment. The use of resistive heating makes it possible to reduce the load on the plasma torch and replace the preliminary drying of waste. The inclusion of additional heating in the plasma installation reduces the time of the technological process and additional operations for the preparation of waste for disposal.

Simulation of heat transfer for the conditions of a mine plasma-resistive furnace is complicated by various electrophysical and physicochemical processes, such as combined heat and mass transfer in a two-phase system. The release of electric power in waste is added to heat and mass transfer. resistive power release in the bypass has a significant effect on the overall process in the PCB chamber. Therefore requires the use of modern numerical methods for modeling the complex physical and chemical process of processing waste.

To date, quite a lot of experience has been accumulated in studying the heat and mass transfer in porous media [1], and electromagnetic processes that occur in electrically conductive media [7]. A theoretical and experimental study of the parameters of the plasma gasifier technological process is presented in [2], design features and operating parameters of plasma generators used in such installations are presented in [8].

The performed research is devoted to the development of a new mathematical model. Investigation of the effect of additional resistive heating on the general distribution of heat and mass transfer during gasification of waste. Study of the influence of additional energy release in the plasma electric furnace chamber on the physicochemical processes of waste gasification.
2. Mathematical model of heat and mass transfer

The general diagram of an electric furnace with combined heating for gasification of municipal solid waste is shown in Fig. 1. The charge (waste) is loaded into the upper part of the electric furnace. Loading is carried out with the specified performance. When loading, the waste has an initial temperature $t_0$. In the lower part of the electric furnace, the plasma torch heats up the gas to the temperature $T_0$. The heated gas flow moves upward to the waste batch. The charge going down is dried, pyrolyzed and gasified. The rising gas stream is saturated with the organic component passing into the gaseous state and water vapor.

In the formulation of the problem, heat and mass transfer will be considered stationary. The cross-sectional shape of the furnace shaft is made of variable cross-section. In the drying zone, it is square, while in the pyrolysis zone, it is conical. In the drying zone, on the entire surface of two opposite walls of the furnace chamber, graphite electrodes are installed that provide current supply to the mass of solid waste charge.

![Figure 1. The schematic diagram of a plasma electric furnace when simulating heat and mass transfer.](image)

A model of thermophysical processes in the chamber of a plasma furnace is described in [7–9], and heat transfer in the charge layer of the drying zone can be described by the system of equations (1-2).

The waste, moving through the mine, is sequentially dried by heated gas, pyrolysis, and gasification of the organic component of the waste. The non-gasified part of the waste in the lower part passes into the slag melt. The oxidizing gas entering from below is saturated with the organic component passing into the gaseous state and moisture.

When organizing a continuous process, the steady-state gas-dynamic and thermal regimes are formed in the furnace chamber. Therefore, the processes of heat and mass transfer in the system of counter-flows of the solid and gas phases can be considered stationary.

As a result of heat and mass transfer between the charge and gas, a temperature field is formed in the charge and the gas stream.

To simulate the heat transfer of the porous structure of the system, a model of two interpenetrating continua is used, which is presented in detail in [2].

Heat and mass transfer of the mixture and the gas phase is described by a system of energy and mass transfer equations:
Energy equation in MSW:

\[
\begin{align*}
(1 - m) \frac{d}{dx} \left[ \lambda_k + \frac{m \cdot d}{(1 - \varepsilon) \cdot d + 1} \frac{d}{dx} \right] \frac{dt}{dx} + q_{Vchem}(x) + q_{Vem}(x) - q_{hl}(x) - G_M \cdot c \cdot \frac{dt}{dx} + \\
+ \alpha_v \cdot F \cdot (T - t) = 0
\end{align*}
\]

(1)

\[
G_{gas} \cdot c_p \cdot \frac{dT}{dx} - \alpha_r \cdot (T - t) = 0
\]

(2)

where \( \alpha_v = 160 \sqrt{\frac{v}{d}} \cdot 0.5 \) is the volumetric heat transfer coefficient; \( \alpha_r = 4 \sigma t^3 \) is the radiation heat transfer coefficient; \( m \) is the porosity; \( \lambda \) is the thermal conductivity coefficient of the pieces of the mixture; \( \lambda_k \) is the contact thermal conductivity coefficient at the contact of pieces; \( d \) is the average size of the piece; \( v \) is the gas velocity; \( T \) is the gas temperature; \( t \) is the temperature of the mixture; \( C \) is the specific heat of the charge; \( c_p \) is the specific heat of gas; \( G_M \) is the specific charge consumption; \( G_g \) is the specific gas consumption; \( x \) is the coordinate along the height of the furnace; \( \varepsilon \) is the degree of blackness of the surface of the pores; \( \sigma \) is the Stefan-Boltzmann constant; \( q_{Vchem}(x) \) is the volumetric specific heat dissipation power due to chemical reactions; \( q_{Vem}(x) \) is the volumetric specific heat dissipation power in the drying zone when an electric current passes through it; \( q_{hl}(x) \) is the reduced volumetric specific power of heat losses through the lining of the electric furnace.

The procedure for calculating the specific heat release \( q_{Vchim}(x) \) in the course of chemical reactions is presented in [2].

To calculate the volumetric specific heat dissipation power \( q_{Vem}(x) \) in the drying zone when an electric current passes through it, the ANSYS finite element modeling software package was used. The obtained distribution of volumetric specific heat dissipation power \( q_{Vem}(x) \) in the form of a matrix of input data is introduced into the model of thermophysical processes described by equation (1).

According to the literature search data, it became known that solid municipal waste has specific electrical resistance. This parameter is about 3-5 Ohm m in the summer. The specific electrical resistance of the waste varies depending on the moisture content in them. Therefore, when conducting model calculations, it was assumed \( \rho_{el} = 1 \div 25 \) Ohm \( \cdot m \). The moisture content of the waste will be from 80% to 20% only in the drying zone. With further passage to other chambers, the chambers of the electric furnace no longer have moisture. Therefore, resistive heating with an industrial frequency current will be realized only in the drying zone. The cross-sectional shape of the drying zone is designed to square to ensure uniform distribution of power \( q_{Vem}(x) \) over the cross-section of the solid waste charge.

The calculation accuracy of thermochemical processes was controlled by changing the grid spacing along the x coordinate and the number of iterations.

3. Research results

Figure 2 shows the dependence of the integrated power released in the drying zone during resistive heating on the voltage applied to the electrodes.
Figure 2. Dependence of the power Rel released in the drying zone on the voltage U at the electrodes during resistive heating:
1 – \( \rho_{el} = 1 \text{Ohm} \cdot \text{m} \);
2 – \( \rho_{el} = 3 \text{Ohm} \cdot \text{m} \);
3 – \( \rho_{el} = 5 \text{Ohm} \cdot \text{m} \);
4 – \( \rho_{el} = 10 \text{Ohm} \cdot \text{m} \);
5 – \( \rho_{el} = 25 \text{Ohm} \cdot \text{m} \).

Figure 3 shows the dependences of the temperature field in a solid waste burden and gas. Shows the effect of resistive heating on the overall temperature distribution in the furnace chamber. As was shown in [7], specific energy consumption significantly depends on the humidity of industrial waste. Figure 5 shows the calculated and experimental dependencies which establish a relationship between the costs required for the processing of waste, and humidity.

Resistive heating is used to dry the waste. Waste moisture is reduced from 60% to 20%. In work [3] it is said that the moisture content of waste of about 20% is necessary. This waste moisture analyzer allows complete waste gasification. Resistive heating, like direct heating, in this plasma-resistive furnace is highly efficient. Its efficiency (excluding heat loss through the lining) is close to 100%. In this case, heating of the drying zone by a gas flow using an indirect method from plasmatrons whose power is transmitted to a plasma-forming gas with an efficiency of \( \approx 80\% \), will be less efficient than that using a resistive method.
As can be seen from Figure 4, when the moisture content of the waste is reduced from 50 to 30%, the specific energy consumption for the processing of waste is reduced by 1.87 times (from 0.75 to 0.4 kW • h / kg). Thus, the implementation of combined plasma-resistive heating of the solid waste charge provides a significant reduction in the specific energy consumption of the plasma torch for the destruction of 1 kg of industrial waste, which is less than 0.4 kW • h / kg (see Fig. 4).

Conclusions
As seen from the calculation and experimental data presented in figure 5, when processing TW with a humidity of 50% and furnace productivity of $G_M = 90$ kg / h, a plasma torch power of $\approx 120$ kW is required. Decreasing TW humidity to 29% will allow reducing the power of the plasma torch to 50 kW.

Therefore, the input of additional power through resistive heating $P = 120-50 = 70$ kW in the drying zone allows reducing the power of the plasma torch by 58%. Besides, reducing the required power of the plasma torch allows increasing the resource characteristics of the plasma assembly unit, switching to plasmatrons with lower working currents and longer lifetime of electrodes.

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