Simulation of heat and mass transfer in a shaft plasma furnace for the processing of municipal solid waste

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Abstract. A mathematical model of the process of heat and mass transfer in two penetrating media (gas stream and waste mixture) during plasma gasification of organic waste is presented in the article. The model takes into account many parameters: the total pressure of the vapor-gas mixture, partial pressure, humidity of the waste, etc. The effect of humidity during heat and mass transfer in the reaction zone of a mine electric furnace on the temperature distribution in the waste charge and the gas phase is shown.

1. Introduction

In the modern world one of the global trends in technology development is the continuous increase in the efficiency and environmental friendliness of carbon-containing wastes management methods. The carbon-containing industrial wastes include: municipal (municipal solid waste (MSW)), agricultural (rice husk, etc.), industrial (wood waste, coal slimes, etc.) and biological (medical, biological sludge deposits (BIO) and etc.)

Despite the different nature of this waste, they all consist of the same chemical elements: carbon, hydrogen, oxygen, nitrogen, chlorine, sulfur, ash (a complex of inorganic elements and compounds), water (moisture), but contain elements and compounds dangerous for the environment (pathogens, heavy metals, etc.).

Influence of carbonaceous wastes on the environment is diverse. This waste has a significant negative impact on the environment: the soil, water, atmosphere, and biosphere.

As shown by the results of the analysis of modern scientific and technical and patent documentation, plasma technologies are being actively developed for the processing of carbon-containing wastes with the production of synthesis gas (fuel gas) using it in the future in power generating devices.

Gasification of carbon-containing waste is a complex physico-chemical process with a large number of effects, a complete scientific explanation of which is far from completion.

Composition carbonaceous wastes can vary over a wide range, which requires a flexible and versatile technology. The main technical problems that are holding back the widespread use of plasma technologies for the processing of technogenic wastes have not yet been solved, namely, the low life of the plasma torches and the high energy consumption for their pyrolysis. A separate question concerns the environmental and safety technology, purification and neutralization of harmful emissions, primarily chlorine. The research is aimed at the development of a mathematical model, software product and technology of gasification of MSW, allowing an increase in the degree of using the energy and raw material potential of waste.
Worldwide, the amount of man-made waste hazardous to population and environment (municipal solid waste, bio-organic waste) annually increases by 2-3 billion tons per year. According to most forecasts, the world energy sector will remain predominantly hydrocarbon in a rather long term. The involvement of carbon-containing waste in the fuel and energy balance of the regions to generate heat and electricity will lead to a decrease in the consumption of natural resources. The most important criterion of the transition to new technologies for waste processing is the reduction of the anthropogenic load on the environment. There are problems with waste disposal: optimal technology for safety, productivity and energy efficiency.

Currently waste recycling using plasma technology is one of the most secure techniques. Worldwide, there are only a few small plants testing plasma technology, the main drawback of which is a very small lifetime of the plasma torch electrodes (up to 100 hours). In Russia, plasma installations for waste disposal are not used. In Russia, there are single copies of experimental samples of plasma installations for processing various degrees of hazardous waste.

Thus, the task of researching energy-efficient and environmentally friendly plasma technology for utilization (gasification) of MSW, the use of waste as alternative energy sources, and environmental protection lies in the area of promising and significant research areas.

To date, a sufficiently large scientific experience has been gained in studying the process of heat and mass transfer in porous media. Among the works in which the processes of plasma gasification of wastes are most thoroughly studied are works [1]. However, the processes of complex heat and mass transfer were not considered. The very process of drying in the electric furnace chamber and its influence on the overall picture of the distribution of temperature fields in the electric furnace chamber was also not taken into account. The development of heat and mass transfer processes is complicated by several processes: the evaporation of moisture from waste during the passage of the heated gas phase through them; exo- and endothermic chemical reactions on the surface of the material and in the gas phase occurring during the gasification of the waste. In the high-temperature zone of an electric furnace, thermal radiation can make a significant contribution to heat transfer.

2. Mathematical model of heat and mass exchange
The development of technology for processing municipal solid waste requires the creation of methods for two main tasks: calculation, heat and mass transfer between two interpenetrating media, taking into account different phase transformations, and energy of chemical transformations of the constituent components of waste.

In reality, waste has a moisture content of up to 60%. During processing, waste in the loading area gets wet, and this moisture is stored only within the drying zone. Further, as the plasma electric furnace moves down the shaft, getting into the pyrolysis zone, the waste should be dried up to 20%, if possible.

The creation of a mathematical model and the simulation of heat and mass transfer in the charge of TKO and the plasma plasma furnace is a complex task. In fig. 1 shows a diagram of a shaft plasma electric furnace for gasification of MSW.

Plasma installation is a cylindrical lined shaft. Thermal energy and oxidizer (air) are supplied to the lower part of the shaft, where the plasma torch is installed.

This type of furnace is most often operated in countercurrent modes, when the processed raw materials are moved downward by natural descent, and the gas flows are directed upwards. The waste entering the gasifier in the upper zone (drying and heating zone), encountering a plasma torch in the lower part of the furnace with a plasma torch, heats and dries, giving away the moisture contained in the heated gas. Further, as the MSW moves into the middle zone (pyrolysis zone), where the temperature reaches 400-800ºС, volatile substances occur due to the decomposition of waste with the release of gaseous hydrocarbons (for example methane, ethylene), liquid hydrocarbons (for example tar), carbon dioxide, etc.
The resulting gases pass through the thickness of the waste into the upper zone of the gasifier, and then they are forcibly sent to the high-temperature zone (the lower part of the shaft), where their decomposition occurs (destruction).

The waste, moving through the mine, is sequentially dried by heated gas, pyrolysis, 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 this process 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 in the gas stream.

To model 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 equations of energy and mass transfer:

- Energy equation in MSW:

\[
\frac{d}{dx} \left[ \lambda_k + \left( \frac{m \cdot d}{(1-\epsilon)} \frac{d}{dx} + \frac{1}{\alpha_l} \right) \right] \frac{dt}{dx} + q_{\text{Vchem}}(x) - q_{\text{h}}(x) - G_M \cdot c \cdot \frac{dt}{dx} +
\]

\[
+ \left[ r + c_{PD} \cdot (T-t) \cdot H \cdot (p_{DG} - p_D^*) \right] \frac{dG}{dx} + \alpha_v \cdot F \cdot (T-t) = 0
\]

Where

\[
\frac{dG}{dx} = -F \cdot \frac{\alpha_v \cdot (p_{DG} - p_D^*) \cdot p}{\rho \cdot c_p \cdot (p - p_D^*)} \cdot R_D \cdot T = \frac{dG_M}{dx} = \frac{dG_{\text{gas}}}{dx}
\]

Figure 1. The scheme of a plasma electric furnace when simulating heat and mass transfer.
\( r \) is the latent heat of vaporization, \( c_{PD} \) is the heat capacity of steam, \( p_{DH} \) is the partial pressure of steam,
\[
H(x) = \begin{cases} 
0, & x < 0 \\
1, & x > 0 
\end{cases}
\]
is the Heaviside function (single jump function),

\( F \) is the cross-sectional area of the mine, \( \rho \) is the density of the vapor-gas mixture, \( c_{p} \) is the heat capacity of the vapor-gas mixture, \( p \) is the total pressure of the mixture, \( p_{D*} \) is the saturated vapor pressure at the charge temperature \( t \), \( c \) is the heat capacity of the wet charge.

Energy equation in steam-gas mixture
\[
G_{gas} \cdot c_{p} \cdot \frac{dT}{dx} - \left[ c_{PD} \cdot \frac{dG}{dx} \cdot H \left( p_{D} - p_{D*} \right) + \alpha_{v} \cdot F \right] \cdot (T - t) = 0
\] (2)

Further development of the study included the inclusion of mass transfer (3-4) in the process of gasification of wastes in the system of heat transfer equations (1-2). This is due to the natural moisture content of the waste.

Equilibrium mass transfer equation
\[
\rho_{w} \cdot \frac{d}{dx} \left( \frac{p_{D*} T}{R_{D}} \right) + \frac{p_{D*}}{R_{D} T} \cdot \frac{dw}{dx} = -F \cdot \frac{\alpha_{v}}{\rho \cdot c_{p}} \cdot \frac{\left( p_{D*} - p_{D*} \right)}{R_{D} \cdot T} \cdot p
\] (3)

The equation of motion for two phases
\[
\frac{p}{R_{D} \cdot T} \cdot \frac{dp}{dx} = -k \frac{dp}{dx}
\] (4)

where \( R_{D} \) is the gas vapor constant, \( k \) is the permeability coefficient of the medium.

The main calculated characteristics of the solution of the system of equations are the temperature distribution in the charge MSW \( t(x) \) and the gas-vapor mixture \( T(x) \) along the height of the shaft of the plasma electric furnace. The system of equations (1-4) is non-linear due to temperature-dependent parameters, coordinates for height and humidity of MSW. One of these parameters is the release of energy from chemical reactions that take place during gasification of MSW, which is related to the temperature dependence of chemical reactions[3-4]. The system of equations (1) - (4) was solved by the finite-difference scheme by the iterative method. The accuracy of the calculations was regulated by changing the step along the coordinate and the number of iterations. To implement the mathematical model and obtain numerical results, a calculation program has been created that allows you to calculate the temperature fields in the plasma electric furnace shaft during gasification of MSW.

3. Research results
Fig. 2 presents the results of calculation of the temperature distributions of gas and charge over the height of the furnace under the influence of the released energy of chemical reactions of the charge especially in the middle of the furnace. This is apparently due to the fact that reactions with the greatest thermal effect occur here. The gas heats up much less, so the temperature fields in the gas coincide with and without chemical sources of heat.
Figure 2. The effect of chemical reactions on heat transfer in the furnace shaft: 1 – gas temperature, 2 – charge temperature, 3 – charge temperature, taking into account the effects of chemical reactions.

Accounting for the effect of mass transfer during the gasification of SMW is clearly visible in Fig. 3, where the results of the calculation of temperature distribution of gas and charge over the height of the furnace shaft are presented.

Figure 3. The temperature distribution of the charge and gas in the space of the electric furnace, depending on the humidity of the waste. Gas temperature at humidity: 1 – 60%, 2 – 40%; charge temperature with humidity: 3 – 60%, 4 – 40%, 5 – 20%.

The release of energy when the moisture content of the mixture is 60% leads to the fact that the temperature of the charge in the drying zone is almost equal to the temperature of gas. This effect is especially significant at the beginning of the drying zone, because evaporating moisture from the waste is added to the charge moisture in the form of heated steam from lower layers. Heated steam mixed with a hot gas stream dries and heats the MSW charge in the drying zone. Further, after passing through the drying zone, a slight cessation of the rise in temperature is seen in the gasification zone.
This is due to the ongoing endothermic and exothermic reactions and an increase in the gas mixture rate. An increase in velocity $w(x)$ is indicated by an increase in the total pressure of the gas-vapor mixture in the electric furnace shaft.

Conclusion
Calculation studies of temperature fields along the height of the furnace, taking into account the effect of mass transfer, showed a significant change in the total heat exchange throughout the working space of the electric furnace during the gasification of waste. The effect of waste moisture on the general distribution profile of the temperature field throughout the furnace shaft was investigated. According to the results obtained, it can be concluded that the drying process of the waste can be carried out directly in the mine of a plasma electric furnace without spending additional electricity.

The proposed model of heat exchange in a shaft electric furnace with plasma heating allows investigation of the influence of the main factors: thermal radiation, chemical reactions, contact heat conduction, and mass transfer process. It can be used to select the required composition of the plasma-forming gas in order to produce synthesis gas of a given composition, determine the dimensions of the furnace for full utilization of the MSW and calculate the required power of the plasma torch, select the place for optimal extraction of synthesis gas from the reaction zone at a temperature of $1200^\circ$C.

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