Simulation of heat and mass transfer in a shaft of plasma electric furnace, when utilizing technogeneous wastes

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Abstract. A mathematical model of heat and mass transfer between counter flows of gas and porous material of man-made waste is presented. The model takes into account the partial and total pressure of the vapor-gas mixture, the radiation heat exchange between the gas and solid phases, the chemical transformations in the individual components of the charge, and the moisture content of the waste is also taken into account. Heat and mass transfer in the chamber of a shaft plasma-ohmic electric furnace was studied for gasification of technogeneous wastes with the use of additional ohmic heating in the drying zone. The influence of ohmic heating on heat and mass transfer is shown not only in the drying zone, but also in the entire shaft of electric furnace.

1. Introduction

Among the environmental problems, the problem of disposing and neutralizing technogeneous waste, including organic ones, whose number is increasing year by year, is acute all over the world. Technogeneous wastes, dangerous for population and environment (solid domestic waste, bio-organic waste) increase annually by 2-3 billion tons per year (According to official data of the Ministry of Natural Resources of the Russian Federation http://rpn.gov.ru/node/854). One of the effective ways for solving this problem is waste gasification in the shaft plasma furnaces with pyrolysis and gasification of the organic part of waste using an electric-arc plasmatron for oxidizer heating and melting the inorganic part. The main disadvantage of these furnaces is high energy consumption. The development of technology for processing of technogeneous waste requires creation of the methods for two main tasks: calculation of heat and mass transfer between two interpenetrating environments, taking into account various phase and chemical transformations of the constituent components of waste, and improvement of energy efficiency. An increase in energy efficiency of such furnaces is currently possible through using combined plasma-ohmic heating for processing the technogeneous waste (TW).

Under the real conditions, waste humidity is up to 60\%. During processing, the waste enters the loading zone in the wet state, and this moisture is kept only within the drying zone. While entering into the pyrolysis zone down the shaft, waste should be as dry as possible. Therefore, it is advisable to organize additional ohmic heating within the drying zone. The development of heat and mass transfer processes under the considered conditions is complicated by several processes: evaporation of moisture from waste, when the heated gas phase passes through it, and release of energy at ohmic heating in the TW material; exo- and endothermic chemical reactions on the material surface and in
the gas phase that occur during waste gasification. In the high-temperature zone of electric furnace, a significant contribution to heat transfer can be made by thermal radiation.

To date, relatively large scientific experience on studying the process of heat and mass transfer in the porous media has been accumulated [1]. Among thorough studies of the processes of plasma gasification of wastes, we can distinguish the works [2, 3]. However, the electric current influence on heat and mass transfer processes has not been considered. The process of drying in the electric furnace chamber and its influence on the overall picture of temperature field distribution in the electric furnace chamber were not taken into account.

2. Mathematical model of heat and mass transfer

Simulation of heat and mass transfer in the charge is a challenge. The scheme of a shaft plasma-ohmic electric furnace for TW processing is shown in Fig. 1.

When modeling, it was taken into account that waste will contain moisture only in the loading zone and within the drying zone until all moisture evaporates under the influence of temperature. Thus, ohmic heating by the current of industrial frequency is possible only in the drying zone. Waste supplied to the pyrolysis zone is dehydrated and has low moisture content.

TW are fed to the upper part of the furnace from the top \((x = H)\), and a gas flow heated in the lower part of the furnace by a plasmatron is raised from the bottom. Wastes, moving through the shaft, are subjected to drying by preheated gas and ohmic heating, pyrolysis, and gasification of the organic component. A part of waste, not subjected to gasification, turns into the melted slag in the lower part. The oxidizing gas, supplied from below, is saturated with an organic component and moisture, turning into the gaseous state.

When organizing a continuous process in the furnace chamber, the steady gas-dynamic and thermal conditions are formed. Therefore, the processes of heat and mass transfer in such a process in the system of counter-current flows of the solid and gas phases can be considered stationary. Due to heat and mass transfer, the temperature field is formed in the charge and gas phase.

Heat and mass transfer in the charge layer can be described by the following system of equations:

Energy equation in the charge
\[
(1 - m) \frac{d}{dx} \left[ \frac{md}{\alpha_1} + \frac{1}{\lambda} \right] \frac{dt}{dx} + q_{Vchem}(x) + q_{Vem}(x) - q_l(x) - \rho \frac{d}{dx} \left[ \frac{dG}{dx} + \frac{q_{Vchem}(x)}{\alpha_1} \right] + \alpha_1 \frac{dG}{dx} + \alpha_1 F(T - t) = 0
\] (1)

where,
\[
\frac{dG}{dx} = -F \frac{c_v}{\rho c_v \alpha_1} \frac{(p_D - p_{DG})}{(p - p_{DG})} R_D T
\]
\[
\frac{dG}{dx} = \frac{dG}{dx} = \frac{dG}{dx}
\]

\[ r \text{ is latent heat of vaporization, } c_v \text{ is heat capacity of vapor, } p_{DG} \text{ is partial pressure of vapor, } \]
\[ H(x) = \begin{cases} 0, & x < 0 \\ 1, & x > 0 \end{cases} \text{ is Heaviside function (single-phase function), } F \text{ is area of shaft cross-section, } \rho \text{ is}
\]
density of vapor-gas mixture, \( c_v \) is heat capacity of vapor-gas mixture, \( p \) is total pressure of mixture, \( p_{DG} \) is pressure of saturated vapor at charge temperature \( t \), and \( c \) is heat capacity of wet charge.

- energy equation of the vapor-gas mixture:
\[
G_c c_p \frac{dT}{dx} - \left[ c_{PD} \frac{dG}{dx} H(p_D - p_{DG}) + c_v F(T - t) \right] = 0
\] (2)

- equation of heat and mass transfer for the vapor-gas mixture
\[
\frac{d}{dx} \left[ \frac{p_{DG}}{R_D T} \right] + \frac{p_D}{R_D T} \frac{dw}{dx} = -F \frac{c_v}{\rho c_v \alpha_1} \frac{(p_D - p_{DG})}{(p - p_{DG})} R_D T
\] (3)

- equation of motion for the entire mixture
\[
\frac{p}{R_D T} \frac{dw}{dx} = -k \frac{dp}{dx}
\] (4)

where \( R_D \) is gas constant of vapor, \( k \) is permeability coefficient of the medium.

Parameters, describing heat transfer in equations (1-2), are considered in detail in [4]. Mathematical description of the processes of electromagnetic field \( q_{Vem} \) in the furnace drying zone, continuous in space and time, are considered in [5].

The main calculation characteristics are as follows: \( t(x) \) is the temperature field in the charge; \( T(x) \) is the temperature field in the vapor-gas mixture; charge consumption \( G_m(x) \) depending on drying (determined by partial pressure, total pressure); consumption of vapor-gas mixture \( G_v(x) \) (determined by partial pressure, total pressure)

Auxiliary characteristics for calculation of drying are: field of partial vapor pressure \( p_{DG} \), field of total vapor pressure \( p \); field of gas mixture velocity \( w(x) \).

The system of equations (1-4) is non-linear due to consideration of parameters that are functions of temperature, coordinate or humidity. For example, such parameters are \( q_{Vchem}(t) \), related to dependence of the chemical reactions rate on temperature [3], power release in the load due to ohmic heating as a function of humidity \( q_{Vem} \); the field of gas mixture velocity \( w(x) \), which is a function of temperature.

Therefore, an iterative method is used to solve this system. The numerical implementation of solution to the system of equations was carried out by the sweep method after conversion of the entire system to the finite-difference scheme. The accuracy of calculations was regulated by the error between the last and previous iteration.

3. Calculation results
Calculation results on distribution of the gas and charge temperature along the furnace shaft height, which demonstrate the effect of ohmic heating on the temperature regime inside the electric furnace,
are presented in Fig. 2. It can be seen that in the drying zone there is a noticeable release of energy inside the charge, dramatically increasing its temperature.

Figure 2. Distribution of charge and gas temperature in the space of electric furnace depending on waste humidity.

Gas temperatures at humidity: 1 - 60%, 2 - 40%;
charge temperatures at humidity: 3-60%, 4 - 40%, 5 - 20%

The release of energy at charge humidity of 60% leads to the fact that the charge temperature in the drying zone is practically equal to the gas temperature. This effect is especially obvious at the beginning of the drying zone because humidity of charge is supplemented with evaporating moisture from the waste in the form of vapor, released in the lower layers. Further, after the drying zone, a slight cessation in the temperature growth is observed in the gasification zone. This relates to ongoing endo- and exothermic reactions and an increase in the velocity of the gas mixture. An increase in the total pressure of the vapor-gas mixture in the electric furnace shaft indicates an increase in velocity w(x).

Figure 3 Temperature field distribution in the shaft of electric furnace with ohmic heating:
1 – gas temperature,
3 – charge temperature;
without ohmic heating
2 – gas temperature,
4 – charge temperature

Distribution of charge and gas temperature along the electric furnace shaft with and without ohmic heating at the same waste humidity (40%) is shown in Fig. 3. It is also necessary to note a small temperature difference between the gas and charge, especially in the drying zone, where heat and mass transfer between the charge and gas-vapor mixture is obvious unlike the other zones of the furnace shaft. This is due to the fact that in other zones of the shaft, there is no evaporation, and the enthalpy flow in gas is much higher than in the charge, so heat removal into the charge has a little effect on a change in the enthalpy flow and, hence, the gas temperature. The same effect is also observed in distribution of the temperature fields without ohmic heating.
4. Conclusions
Calculations of temperature distribution along the furnace height with consideration of ohmic heating and mass transfer effect have shown a significant effect on heat transfer inside the electric furnace shaft.
Inhomogeneous heat release due to ohmic heating with a pronounced effect at the beginning of the drying zone with a sharp increase in the charge temperature is shown.
Analysis of results shows that ohmic heating of wet waste in the upper part of the shaft electric furnace is an analog of the preliminary technological process of waste drying before loading into the furnace aimed at reduction of specific energy consumption for gasification of the organic component of mixed wastes. As it is shown in [6], it is possible to increase substantially the resource characteristics of plasmatron operation, reducing its loading [7].

ACKNOWLEDGMENTS
The work was financially supported by the Ministry of Education and Science of the Russian Federation according to the Subsidiary Agreement No.14.607.21.0118 (unique project identifier RFMEFI60715X0118)

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