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METHODS OF PARAMETERS CALCULATION FOR WASTES HIGH-TEMPERATURE PLASMA PROCESSING

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Abstract. The article presents the methodology of plasma parameters calculation for different ratios of its constituents and taking into account that plasma jet is both a source of thermal energy and a part of initial reaction mixture for various physical and chemical transformations, in particular, those associated with processing of different solid wastes. As the methodology application example carbon conversion by steam-and-air plasma jet is investigated.

Keywords: plasma, plasma-forming mixture, thermodynamic analysis, steam-air conversion, solid wastes.

1. Introduction

In the recent years there has been a trend towards greater use of high-temperature plasma technology for recycling of various wastes, including highly dangerous (organochlorine, infected medical, *etc*.) ones. Plasma energy sources are used very efficiently for gasification of various organic materials in order to obtain energy carriers, syngas, and protective atmospheres [1–4].

The use of low-temperature plasma jet as a source of external heat and the reaction components in the various processes requires knowledge of its basic quantitative indicators.

Depending on requirements to end product of different solid wastes processing the plasma jet can be formed both by using only water vapor (saturated or superheated) as well as with the use of water vapor and air in a certain proportion. In the last case not only atmospheric air can be used, but also the air enriched with oxygen, up to the use of technical oxygen.

Variation of plasma jet composition makes it possible to most rationally and economically organize processing of various solid wastes (including especially dangerous, in particular, infected medical ones) taking into account their specific composition as well as additional requirements to manufactured products composition. Also consideration of both possible composition variations of processed material as well as of the set of reactions that describe physical and chemical transformations is necessary.

Therefore, the composition of plasma jet must satisfy the requirements which in the first approximation depend on the stoichiometric coefficients of the reactions (transformations) under study.

At the same time it is also necessary to take into account the energy component of the processes, which determines the actual temperature in the reaction volume.

Rational choice of the mentioned plasma jet constituents eventually determines obtaining of the final products of specified composition under minimally necessary energy consumption.

The presented preliminary computations make it possible to determine the total and component-specific mass flow for plasma jet of given thermal power depending on desired temperature and ratio of mixture constituents.

2. Calculation of Plasma Jet Parameters

Since at high temperatures the dissociation and ionization processes take place the calculation is based on the energy balances method with the use of total enthalpy of initial components and plasma jet of a given temperature.

Calculation of enthalpies was carried out by means of automated system of thermodynamic calculations "TERRA" [5]. The initial enthalpy of water vapor corresponded to the total enthalpy of saturated water vapor at the temperature of 373 K, and the enthalpy of air – to the total enthalpy at 293 K.

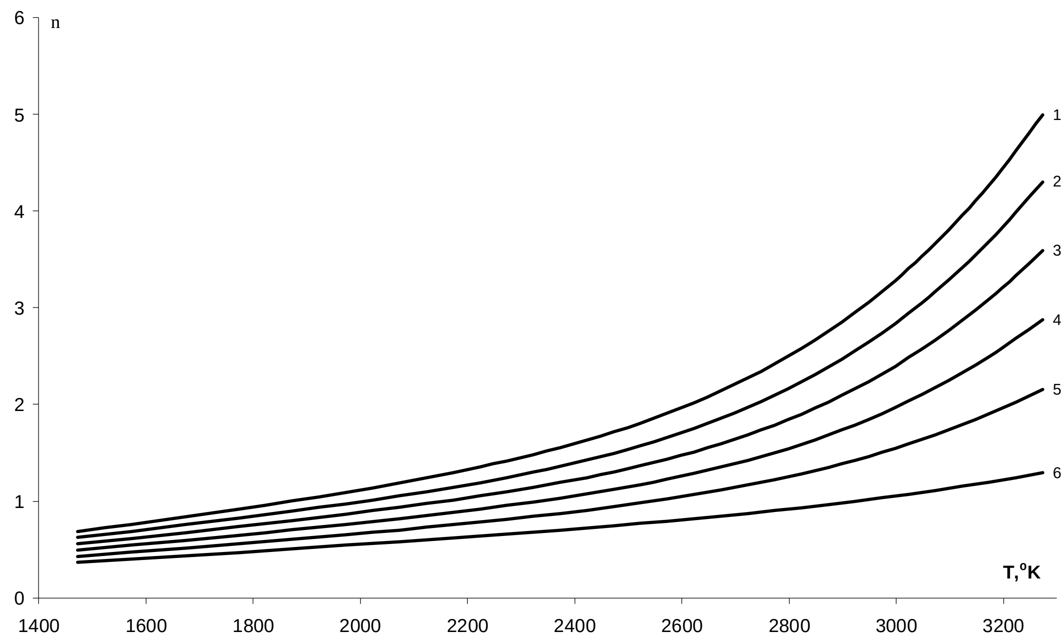

Fig. 1. Specific energy consumption $n = W/G$ for a given temperature of plasma jet at different water vapor/air ratios: $\gamma = 1$ (1); $\gamma = 0.8$ (2); $\gamma = 0.6$ (3); $\gamma = 0.4$ (4); $\gamma = 0.2$ (5) and $\gamma = 0.0$ (6)

In accordance with the plasma recycling processes conditions the calculation of total enthalpy was carried out in the range of 1473–3273 K for different percentages of water in the initial mixture.

The calculated value of energy (heat) $\Delta I(t_k)$ (kJ/kg) which is necessary for heating of 1 kg of the initial mixture from start state to the given temperature permits to define the general and component-wise mass flow of plasma jet (kg/s) by using plasmatron of the given thermal power of W (kW):

$$G_{sum}(t_k) = W/\,\Delta I(t_k)$$
$$G_{H2O}(t_k) = \gamma \cdot G_{sum}(t_k)$$
$$G_{O2}(t_k) = (1-\gamma)\cdot G_{sum}(t_k)\cdot \eta$$
$$G_{N2}(t_k) = (1-\gamma)\cdot G_{sum}(t_k)\cdot(1-\eta)$$

where γ – mass fraction of water vapor in the plasma jet ($0 \le \gamma \le 1$); η – mass fraction of oxygen in the air used for the formation of the plasma jet.

For a 100 kW plasmatron calculations for various water/air ratios in the plasma jet when using air ($\eta = 0.23$) and oxygen enriched air ($\eta = 0.55$) were performed.

Since using plasmatrons of other capacity causes only proportional change in plasma mass flow the received data permit to graph the temperature dependence for the specific energy consumption $n = W/G$ (kW·h/kg), which must be expended to obtain plasma jet of the desired temperature for different ratios between water vapor and air (atmospheric or enriched by oxygen). Fig. 1 illustrates the mentioned dependence for different (water vapor) / (atmospheric air) ratios. The obtained results can be used to evaluate the plasma parameters (flow, temperature) at the outlet of the plasmatron prior to its contact with recyclable material, because the temperature in the reaction chamber after the contact of plasma jet with the processed material may substantially differ from the temperature of the plasma prior to contact. In addition, knowledge of these parameters makes it possible to assess the feasibility of the selected mode of plasma material processing taking into consideration the power density constraints of plasmatron.

3. Some Peculiarities of Processed Material Components Total Enthalpy Computation

The procedure of thermodynamic calculation does not permit to divide the components of the common material flow onto input flow of plasmatron and the input flow into reaction chamber. The main difficulty is to determine the total enthalpy of the flow inlet substances.

As for dry components enthalpy of recyclable materials, the reference data [5-7] can be used, and in their absence – other kinds of evaluation. In particular, for a number of substances, which consist primarily of hydrocarbons, for indirect determining of their standard enthalpy an approach based on the use of Mendeleev's formula for calculating the combustion heat of substances was chosen [8].

Additional difficulties arise when assessing the share of total enthalpy flow brought in by the water present in one form or another.

When processing certain groups of wastes materials there is a necessity in adding as a reactant some amount of additional water in the form of superheated to a given temperature vapor. Mainly it is connected with desire to suppress formation of soot, which is undesirable for many reasons, when the soot is not a target product.

The maximum quantity of steam which can be fed directly to plasmatron inlet is limited by the plasmatron capacity and is decreasing with increasing of plasma jet temperature. This amount of water may be insufficient to move the conversion process into desired direction.

As was mentioned above, at thermodynamic calculation (such as direct use of "TERRA") there is no possibility to consider separately the indicated flows of steam having different enthalpies. Therefore, when setting the initial data for the calculation, these streams of water vapor were treated as a common stream with the enthalpy of water vapor at 373 K. In this case, the amount of energy which plasma jet introduces into the reaction chamber according to the thermal capacity plasmatron must be increased by the amount of energy that was expended in external heating (overheating) of water vapor from 373 K to the one at which it is fed to the reactor .

Thus, if the mass flow of additional steam heated up to the temperature of t_{ad} (K) is equal to G_{H2Oad} (kg/s) this means that the energy flow of the following capacity is additionally fed into reactionary volume:

$$\Delta_{ad} = G_{H2Oad} \cdot (I(t_{ad}) - I(100)),\ \text{kW}$$

where $I(t_{ad})$, $I(100)$ –total enthalpy of steam at the temperatures of t_{ad} and 373 K, respectively.

In addition to the water vapor with the plasma jet and additional water vapor which comes directly to the reactionary volume a part of water in the condensed state enters the reactionary volume directly with the processed material at the temperature of the latter.

In this case it is necessary to take into account that a part of the energy coming to the reaction volume will be spent on heating a specified amount of water to the temperature of 373 K and its subsequent evaporation.

Thus, if the mass flow of condensed water, which comes with the processed material at the temperature t_m (K), is equal to G_{H2Om} (kg/s) this means that the total energy which is coming in with the plasma jet and the additional vapor stream entering reaction volume must be diminished by Δ_m of energy spent on heating and evaporation of water at the temperature of 373 K:

$$\Delta_m = G_{H2Om} \cdot (c_{H2O(l)}\,(100 - t_m) + \Delta Q_{H2O},\ \text{kW}$$

where $c_{H2O(l)}$ and ΔQ_{H2O} are specific heat capacity and vaporization heat of water, respectively.

In the same way additional heating of dry part of processed material can be considered.

4. Plasma Steam-and-Air Conversion of Solid Carbon

As an example the process of plasma treatment of solid carbon – C(c) is considered for producing of "synthesis gas" – a mixture of CO and H_2.

This process involves oxidation of the free carbon by the oxygen of the plasma jet, as well as steam conversion of carbon.

The indicated reactions look as follows:

$$C + 0.5 \cdot O_2 = CO$$

$$C + H_2O = H_2 + CO$$

From the stoichiometry of the reactions it follows that if in the plasma-forming mixture the mass flow rate of oxygen is G_{O2}, of nitrogen – G_{N2} and of water – G_{H2O} then the flow of processed carbon must be equal to:

$$G_C = 3/4G_{O2} + 2/3G_{H2O}$$

Let mass oxygen concentration in dry (or oxygenated) air be equal to Z_{O2}, Z_{N2} = 1-Z_{O2}. If the portion of water in the plasma-forming mixture is γ then the concentration of components in the plasma source is equal to:

$$Y_{H2O} = \gamma,\ \ Y_{O2} = (1-\gamma) \cdot Z_{O2},\ Y_{N2} = (1-\gamma) \cdot Z_{N2}$$

After adding of carbon in the marked ratio in reactionary volume, part of plasma α in the total flux which comes into the reactionary volume equals

$$\alpha = 1/(1 + 3/4Y_{O2} + 2/3Y_{H2O})$$

and the concentrations of components of this stream equal to:

$$X\text{c} = \alpha \cdot (3/4Y_{O2} + 2/3G_{H2O})$$

$$X_{H2O} = \alpha \cdot Y_{H2O}$$

$$X_{O2} = \alpha \cdot Y_{O2}$$

$$X_{N2} = \alpha \cdot Y_{N2}$$

In case of thermodynamic calculation of the process of solid carbon plasma processing the total enthalpy of the input flux is defined mainly by water vapors at 373 K (enthalpy of carbon, oxygen, and nitrogen at 293 K can be neglected) and equals

$$I_{in} = -13282.5 \cdot X_{H2O}$$

Thermodynamic calculation allows to define the value of total mass flux G_{sum} with the initial concentration of Xc, X_{H2O}, X_{O2}, X_{N2} which can be processed using plasmatron of W capacity.

$$G_{sum} = W/(\ I(t^*) - I_{in}),\ \ \text{kg/s}.$$

where $I(t^*)$ – total processing products enthalpy at the selected temperature of t^* at the reactor output.

This amount corresponds to the total flux of plasma-forming components, which is equal to:

$$G_{pl} = \alpha \cdot G_{sum}$$

Consequently, according to Fig. 1 (or similar one when using air enriched with oxygen) and value of $n = W/G_{pl}$, plasma temperature at plasmatron output – reactionary volume input can be determined.

The given temperature of t^* should correspond to the temperature at which concentration of residual solid carbon C(c) becomes less than the given value ($\approx 10^{-10}$), *i.e.* should correspond to the condition of full processing of the initial material.

The performed calculations allow to simultaneously define carbon plasma processing products concentration and, if necessary, to select such ratio of plasma-forming components which provides necessary composition of processing products. As a rule, this is the ratio between concentration of monoxide (CO) and hydrogen (H_2).

Below the results of carbon processing using the plasmatron of W = 100 kW capacity and air as plasma-forming component (Z_{O2} = 0.23, Z_{N2} = 0.77) for different values of γ are presented.

Example 1: γ = 0.9 (Fig. 2)

Y_{H2O} = 0.9, Y_{O2} = 0.023, Y_{N2} = 0.077

α = 0.618334

X_C = 0.381666, X_{H2O} = 0.5565,

X_{O2} = 0.014222, X_{N2} = 0.047612

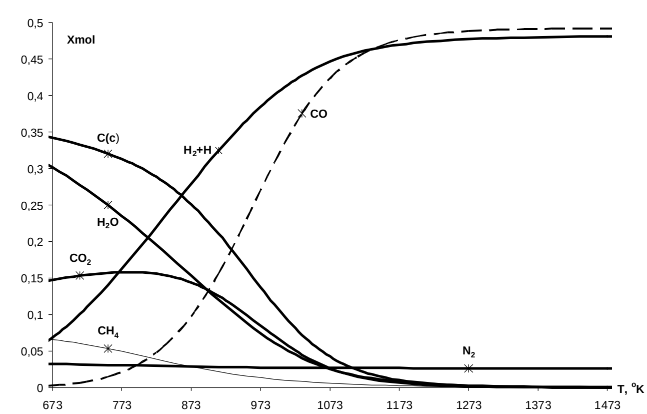

Fig. 2. Dependence of the reaction product concentrations on the temperature in the reaction volume, γ = 0.9

According to the calculated data, at the temperature t^* = 1473 K concentration of solid carbon residual is less than 10^{-10}. This temperature corresponds to the total flux G_{sum} = 16.0491 g/s (57.777 kg/h) and plasma-forming components (plasma) flow equals G_{pl} = 9.924 g /s (35.725 kg/h). Therefore, performance of carbon processing equals G_C = 6.125 g/s (22.051 kg/h).

At such plasma-forming flow the specific energy consumption equals n = 2.799 and according to Fig. 1 the plasma jet temperature at inlet into the reaction volume equals t_{pl} = 2934.8 K. Volume (molar) ratio of CO/H_2 = = 1.023 with the total flux rate of G_{CO} + H_2 + H = = 15.2525 g/s (54.909 kg/h).

Example 2: γ = 0.5 (Fig. 3)

Y_{H2O} = 0.5, Y_{O2} = 0.115, Y_{N2} = 0.385

α = 0.70443

X_C = 0.29557, X_{H2O} = 0.35222, X_{O2} = 0.08101,

X_{N2} = 0.27121

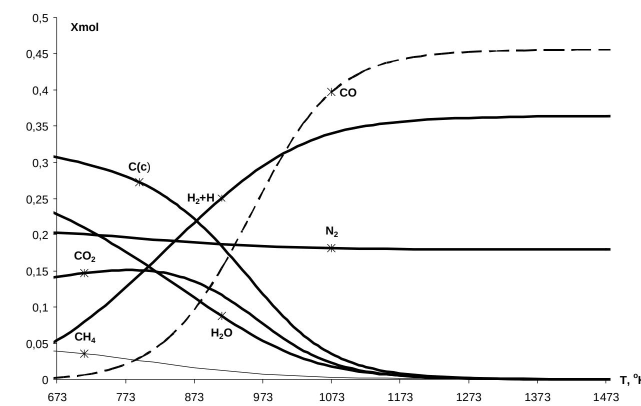

Fig. 3. Dependence of the reaction product concentrations on the temperature in the reaction volume, γ = 0.5

According to the calculated data, at the temperature t^* = 1423 K concentration of solid carbon residual is less than 10^{-10}. This temperature corresponds to the total flux G_{sum} = 25.999 g/s (93.595 kg/h) and plasma-forming components (plasma) flow equals G_{pl} = 18.314 g/s (65.931 kg/h). Therefore, performance of carbon processing equals G_C = 7.640 g/s (27.664 kg/h).

At such plasma-forming flow the specific energy consumption equals n = 1.517 and according to Fig. 1 the plasma jet temperature at inlet into the reaction volume equals t_{pl} = 2701.9 K. Volume (molar) ratio of CO/H_2 = = 1.252 with a total flux rate of G_{CO} + H_2 + H = = 18.902 g/s (68.047 kg/h).

5. Conclusions

On the basis of energy balances method using the total enthalpy of the initial components and of resultant plasma jet of a given temperature the technique and corresponding mathematical support were elaborated for calculation of the parameters of low-temperature plasma of required power for different ratios of plasma-forming components.

Variation of plasma jet composition makes it possible to most rationally and economically process various solid wastes (including those especially dangerous, in particular, infected medical ones) with taking into account their specific composition and a set of additional requirements to the final products composition of processing.

The developed software allows to quickly execute alternative calculations of plasma processing processes of solid waste of different origin with using, in general case, different plasma-forming components.

The rational choice of plasma jet components eventually defines obtaining of processing products of the given composition at minimum necessary energy consumption.

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МЕТОДИКА РОЗРАХУНКУ ПАРАМЕТРІВ ВИСОКОТЕМПЕРАТУРНОГО ПРОЦЕСУ ПЛАЗМОВОЇ ПЕРЕРОБКИ ВІДХОДІВ

Анотація. *У роботі запропоновано методику розрахунку параметрів плазми при різних співвідношеннях компонентів, що її утворюють, з урахуванням того, що плазмовий струмінь є не тільки джерелом теплової енергії, а й складовою частиною вихідної реакційної суміші для проведення різних хімічних та фізичних перетворень, зокрема, пов'язаних з переробкою твердих відходів різного походження. Як приклад застосування методики розглядається процес пароповітряної плазмової конверсії вуглецю.*

Ключові слова: *плазма, плазмоутворююча суміш, термодинамічний аналіз, пароповітряна конверсія, тверді відходи.*