Effectiveness of the Plasma Neutralization Technology for Supertoxicants

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Abstract. The plasma neutralization technology for the products of thermal waste processing—supertoxicants (polychlorinated dibenzodioxines, dibenzofurans, biphenyls, etc.)—is investigated. The problem of supertoxicants formation in the process of thermal processing for household and industrial waste of different composition is identified. To solve this problem, we propose the use of plasma generators in environmental technologies, in which due to the high-energy plasma effect on substances of different phase compositions, their deep decomposition (plasma incineration—"burning") occurs. Known methods of thermal neutralization of dioxins are considered. Temperature approximations of the decomposition time for dioxins in the temperature range of plasma heating are found. Efficiency criteria of plasma heating and neutralization are introduced. The modernized design of the plasma torch for utilization of gaseous waste of supertoxicants processing is offered. The gas-dynamic parameters of the air-plasma flow in the process of thermal heating by a plasma jet are determined by the methods of mathematical modeling. Efficiency of the considered technology of plasma incineration is proved.

Keywords: Plasmatron · Design · Efficiency · Environmental safety · Recycling · Ecological safety · Decontamination · Incineration · Plasma torch

1 Introduction

One of the problems currently facing developers of environmental technologies is the formation of supertoxicants (polychlorinated dibenzodioxides, dibenzofurans, biphenyls, etc.) in the process of thermal waste processing. One solution to this problem is the use of plasma torches for these purposes [1], in which due to the high-energy plasma effect on substances of different phase compositions, their deep decomposition occurs—plasma incineration ("burning") [2]. The introduction of plasma torches at the afterburning stage of gaseous products of hazardous waste processing is rational. Similar technologies using DC arc plasma torches were proposed by the authors earlier [3–6].

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To assess the effectiveness of such methods, dioxins were selected, which are formed as by-products in pulp and paper, chemical, metallurgical, waste processing, and other industries (especially chlorine and bromine) [7]. In addition, they are formed in the process of high-temperature incineration of waste together with fuel in furnaces of stationary or mobile type. It is possible to reduce the content of dioxins in the exhaust gases by means of activated carbon [8] injected into the bag filter, or by installing special layer filters used, for example, in Hitachi Zosen Inova installations, which are currently being introduced in Russia [9]. At the same time, however, there is a problem of disposal of contaminated activated carbon. For this reason, it is widely accepted that the mandatory element of furnaces for waste burning is the afterburning chamber, necessary for the complete destruction of dioxins.

2 Technique of Researches

According to the results of recent studies [10], we can conclude that for the purpose of preventing the formation of dioxins in the combustion zone should adhere to the following process parameters: temperature above 1150–1300 K, the residence time of the waste in the combustion zone at least two seconds, and 6% excess oxygen in the gas mixture; in the cooling zone, the temperature range is 500–800 K and a residence time is not exceeding 1 s. Based on a small amount of known information on high-temperature neutralization of dioxins [11] (at temperatures of 15,000 and 50,000), the authors made approximations of the temperature dependence of the required time of their decomposition. The search for approximation dependencies was carried out on the basis of the Arrhenius equation for the reaction rate constant:

$$k = k_0 \cdot e^{-E/\mathrm{RT}}, \tag{1}$$

where k_o and E depend on the nature of the reagents and E is the activation energy.

Since the decomposition time and the reaction rate are inversely proportional, the search was carried out using equations of two types (with a constant and temperature-dependent pre-exponential factor):

$$t = t_0 \cdot e^{-E/\mathrm{RT}}, \tag{2}$$

$$t = t_0(T) \cdot e^{-E/\mathrm{RT}}. \tag{3}$$

As a result, two equations were obtained:

$$t = 1.28 \cdot 10^{-5} \cdot e^{18/T}, \tag{4}$$

$$t = \frac{7.2 \cdot 10^{-5}}{T^{3/2}} \cdot e^{21.7/T}, \tag{5}$$

where $[t] = \text{sec}$, $[T] = \text{thousand K}$, with an activation energy $E = 150 \div 180$ kJ.

On the basis of the obtained equations, the following estimates of the required time for their decomposition were made (Table 1).

Table 1. Temperature dependence of the decomposition time for dioxins (estimation)

T, thousand K		1.5	2	2.5	3	3.5	4	4.5	5	5.5
t, msec	by Eq. (4)	2000	100	20	5	2	1.2	0.7	0.5	0.3
	by Eq. (5)	2000	1300	110	20	5	2	0.9	0.5	0.3

Since in the process of plasma heating, the volume of the gas mixture passing through the mixing chamber of the plasma torch warms up unevenly (at different temperatures and at different times), it makes sense to introduce universal criteria for the efficiency of the decomposition for dioxins. It is obvious that both the temperature and the heating time increase in efficiency, and also taking into account the activation mechanism of decomposition reactions, the following criteria were derived on the basis of the obtained approximating dependences:

$$\mathrm{RT} \cdot \ln(t/t_{10}) > E, \tag{6}$$

$$\mathrm{RT} \cdot \ln(T^{3/2} \cdot t/t_{20}) > E. \tag{7}$$

The following expressions can be used as numerical criteria for evaluating effectiveness:

$$C1 = T \cdot \ln(t/t_{10}), \quad C1 > 18, \tag{8}$$

$$C2 = T \cdot \ln(T^{3/2} t/t_{20}), \quad C2 > 21.7 \tag{9}$$

where $[t]$ = sec, $[T]$ = thousand K, $t_{10} = 12.8$ μsec, $t_{20} = 72$ μsec.

Since there are no reliable data on the decomposition time of dioxins in the entire studied temperature range, it is advisable to use not the data of Table 1, but both the proposed criteria *C1* and *C2* when evaluating the heating efficiency.

It is obvious that the technology of plasma afterburning of gaseous wastes proposed by the authors should, at a minimum, provide the required time of the gas flow of hazardous wastes at the appropriate temperature set by heating the mixing chamber (MC) of the utilized and plasma-forming gas flows by plasma arc (jet). Similar technology (Fig. 1a), as is known [12], was developed on the basis of a patented model of an arc plasma torch [13] with its subsequent modernization for neutralization of toxic vapor-gas flows of different compositions and phase states. The plasma jet is formed in the MC by the interaction of the plasma arc excited and burning between the cathode and the anode of the nozzle unit of the plasma torch, with the vortex flow of the plasma-forming gas (PFG) and its subsequent blowing into the MC due to the high kinetic energy of the PFG flow (Fig. 1b). The new design of plasma torch is characterized by the presence of a mixing chamber (MC), in which the mixing and heating of the flows of the tangentially supplied toxic vapor-gas mixture and PFG flow pre-swirled with the help of a gas-vortex stabilization system are provided. The nozzles for supplying the secondary (recycled) flow are located on the replaceable part of the plasma torch, or can be carried out beyond it and located under the nozzle section at any angle to the axis of the plasma jet (Fig. 1a).

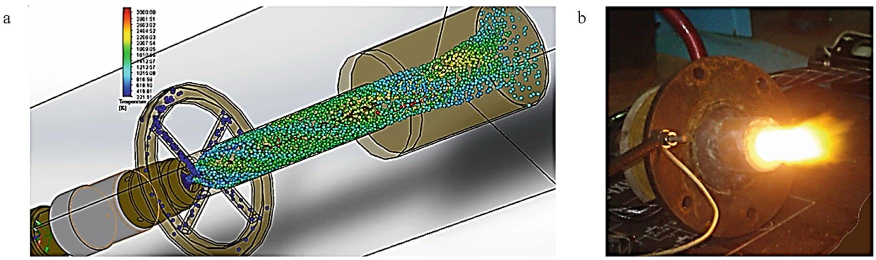

Fig. 1. The plasma torch for the hazardous waste neutralization: **a** calculation model, **b** experimental model.

The estimation of efficiency for heating of a gas-air mixture in MC was made by calculation of gas-dynamic parameters in the application FlowWorks of the SolidWorks software with variable value of a grid discretization. Gas-dynamic modeling was carried out at the mass flow rate of the PFG 0,011 kg/s and the diameter of the inlet hole in MC 4 mm (typical for the effective gas-vortex stabilization of the arc plasma torch). The calculation of temperatures in the MC was carried out on several rectilinear trajectories (lines) of different distances from the axis of the chamber (Fig. 2a) at the characteristic air-plasma arc (jet) temperature of 7000 K. As the calculations showed, the main flow of the utilized gas moves in the MC along a spiral trajectory (Fig. 2b), and therefore estimates of the kinematic parameters were made along the characteristic spiral line. In accordance with the velocity distribution in the mixing chamber, the parameters of the spiral line along which the recycled gas flow predominantly moves were selected: diameter—5 cm, pitch—8.5 cm, and length of one spiral—20 cm. Since the spiral nature of the gas flow calculation of the rectilinear trajectory leads to strong oscillations of parameters along the line of motion, also used the calculation of the average cross-section of the MC temperatures and velocities.

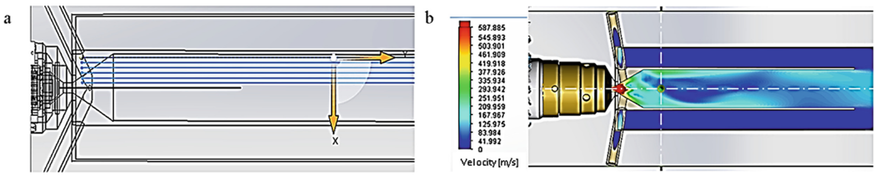

Fig. 2. Calculation of gas-dynamic parameters in the plasma torch system: **a** trajectory calculation of speed and temperature in the MC; **b** temperature distribution.

In the initial calculations, the technological scheme was analyzed with the supply of the secondary flow of the utilized gas through two axisymmetrically arranged nozzles at angles of 10°, 20°, and 30° to the axis of the plasma jet with a length of 90 mm, with a mass flow rate of 0.005 kg/s for each tube. Geometry of MC: length not less 150 mm, the angle of primary parts disclosure—20º, disclosure on the rest part of MC: for cylindrical—00, for confusor—5°.

The results of the gas-dynamic parameter (temperature, speed, and heating times) calculations for the utilized gas in various areas of cylindrical- and confusor-type MC showed that heating occurs at average temperatures 1500–4000 K and average speeds in 50–100 m/s at typical heating times 2–5 ms. In the confusor type, the heating time increases by 1.5–2 times depending on the trajectory, with the greatest increase occurring near the walls of the MC. The latest results correlate with the orders of magnitude of the decomposition time for dioxins at such temperatures (Table 1) and indicates the possibility of using the method of plasma afterburning of hazardous waste processing.

At the next stage, the upgraded constructive scheme was considered. Supply of the utilized gas in this scheme is on a tangent to a stream of PFG by four channels (diameter 4 mm) located perpendicularly to an axis of MC at distance of 11 mm from a nozzle unit (Fig. 1a). This scheme was chosen in order to assess the efficiency of the technology at a higher productivity (increasing the volume of recycled gas). For comparative analysis, we selected comparable process parameters: the consumption of PFG—0.005 kg/s, the consumption of gas utilized by channel—0,004 kg/s, and the temperature of the air-plasma arc—7000 K. In order to ensure effectiveness, it was reviewed by two options of heating: by « short » plasma jet with a length of 90 mm (similarly to the previously discussed technologies) and « long » plasma arc of 170 mm. It is obvious that the latest version requires twice as big power supply of power source for plasma arc. Geometry of such MC: length not less 170 mm, the angle of primary parts disclosure—20°, and disclosure on the rest part of MC—0° (cylindrical configuration).

3 Results of Research and Their Discussion

When calculating along the spiral trajectory, significantly smaller oscillations of gas-dynamic parameters were observed, which confirms the preferential distribution and nature of the movement of the disposed gas in the MC. In the approximation of the spiral trajectories, the evaluation of the heating time shows a twofold increase for the most remote from the axis trajectories, and about half the rise in average temperature along the path, which for the recyclable gas flow is 3–5,5 thousand K (Fig. 3a).

The analysis of the presented results allows us to conclude that the increase in the length of the plasma jet in the MC leads to an increase in the gas velocity (Fig. 3b), which naturally affects the reduction of heating time (Fig. 4a). However, the average temperature of the gas everywhere in MC increases by about 500 K (Fig. 4b), resulting in the efficiency of dioxins decomposition which is 30–40% higher (according to criteria *C1* and *C2*). Similar conclusions can be made in the analysis of gas-dynamic parameters and heating temperatures, made along the spiral, which, as noted earlier, corresponds to the movement of the recycled gas in the MC.

Comparison with the previously obtained results [12] also demonstrates the advantages of the upgraded technology. Figure 5 shows the results of the calculation of linear trajectories which shows an increase of 13% (when heated by a jet of 170 mm) and 35% (with a comparable length of the jet of 90 mm) heating time at comparable heating

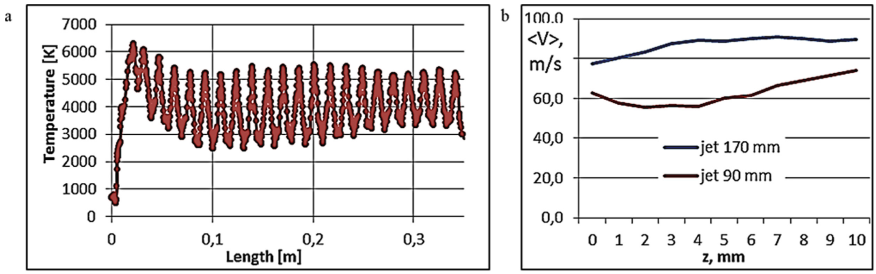

Fig. 3. Distribution of calculated parameters in the MC of plasma torch: **a** temperature along the spiral trajectory (plasma jet length 170 mm); **b** velocity along rectilinear trajectories in MC under heating by short (90 mm) and long (170 mm) plasma jet.

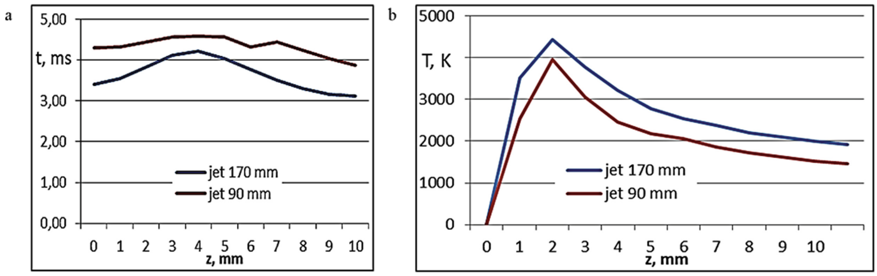

Fig. 4. Distribution of calculated parameters along rectilinear trajectories in MC of plasma torch under heating by short (90 mm) and long (170 mm) plasma jet: **a** heating time; **b** temperature.

temperatures. Process efficiency estimates made according to the introduced criteria, *C1* and *C2* (Fig. 6), talk about increasing efficiency for upgraded technology. Evaluation by criterion *C1* shows the efficiency of the process both when heated by a short (90 mm) and long (170 mm) plasma jet. More stringent requirements (simultaneous implementation of criteria *C1* and *C2*) clearly determine the need for a long (170 mm) plasma jet for neutralization of dioxins. It should be noted that the calculations made along the spiral trajectory demonstrate the maximum values of the process efficiency (Figs. 5 and 6). It is obvious that the further direction of the considered technology improvement should become its constructive optimization according to integral criteria of neutralization efficiency and profitability. In this regard, the following parameters should be considered: the consumption of gas flows, the angles of the supply for utilized gas, the geometry of MC, and the power supply of source power, providing plasma jets of required length in the MC. It is also advisable to provide a quenching chamber before the emission of gases into the atmosphere when designing the neutralization technology.

4 Conclusions

The results of the analysis presented in this paper indicate the validity of this neutralization method on the example of one of the most dangerous supertoxicant—dioxin. This technology, as noted earlier [12], has significant advantages over the known technologies

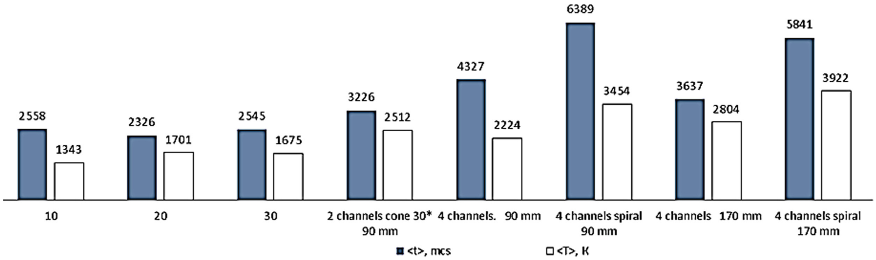

Fig. 5. The average values of time and temperature for different designs of MC.

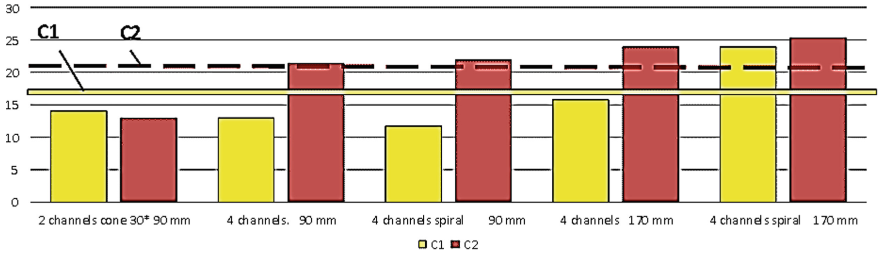

Fig. 6. Criteria of the heating efficiency for different designs of the MC.

of high-temperature combustion and waste disposal due to the speed and efficiency of the process. However, the development and analysis of this eco-technology should be continued in order to find the optimal parameters for its application.

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