Journal of Engineering Physics and Thermophysics, Vol. 81, No. 3, 2008

TESTING AND CALCULATING A TWO-CHAMBER PLASMA FURNACE FOR PROCESSING OF RADIOACTIVE WASTES

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UDC 261.039.7:533

A two-chamber plasma furnace has been tested and the advantages of the processing of radioactive wastes with the use of plasma-thermal technologies have been demonstrated. A model of a plasma furnace for processing of low- and medium-activity radioactive wastes formed in the process of operation of atomic-power and nuclear-industry plants has been developed. The thermal parameters of such a furnace have been calculated.

Introduction. Wastes containing radionuclides or contaminated by them are formed in processes involving the use of radioactive materials. Among such works are, first of all, the operation of atomic-power and nuclear-industry plants, the removal of these plants from operation, and the use of radionuclides in the industry, medicine, and scientific investigations. Radioactive wastes are also formed in the process of deactivation of territories contaminated as a result of technological works, an accident, or the processing of natural raw materials.

In the process of operation of nuclear-power and nuclear-industry plants as well as in the case of eliminating of the consequences of radiative accidents and performance of scientific-research works, large amounts of solid and liquid radioactive wastes of low and medium activity are formed. Among these wastes are working clothes, individual protective means, rags, paper, timbers, building materials, packages, different equipment, pottery works, glass works (for example, laboratory vessels), rubbers, polymeric and plastic materials, products of metals and alloys, waste ionizing radiation sources, materials from vivisection centers (beddings and so on), dead experimental animals, gas-purification-system filters, soils, rocks, and ion-exchange resins.

The average composition of the wastes formed in the process of operation of an atomic-power plant (APP) is presented in Table 1.

Processing of Radioactive Wastes. The processing of radioactive wastes involves the preliminary treatment of these wastes, their conditioning, and obtaining, in the long run, materials with properties satisfying the requirements of their burial. The processed radioactive wastes should be safe for handling, transportation storage, and burial. The type of processing of radioactive wastes is determined by their characteristics and the general state strategy of treatment of wastes. The main challenge of the processing of radioactive wastes is to decrease their initial amount to a minimum value and to transform the products obtained into a stable chemical state.

The gathering and initial packing of radioactive wastes directly where they were formed are carried out in accordance with the national rules and corresponding local instructions. The main purpose for processing radioactive wastes is to transform them for safe storage with respect to environment and economic factors. The amount of radioactive wastes subjected to processing decreases depending on the processing concept selected. The processing of radioactive wastes can be made easier by their preliminarily preparation or treatment.

Thermal Treatment of Radioactive Wastes. Thermal treatment of radioactive wastes involves a number of oxidization and pyrolytic processes for decreasing the amount of solid combustible wastes [1]. These processes substantially decrease the volume (100:1) and mass (10:1) of the wastes due to the chemical destruction of their organic component that is a dominant part of them. With the use of thermal methods a wide range of wastes, including dry and moist solids, organic liquids, and even wastes in aqueous solutions can be treated.

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TABLE 1. Composition of the Wastes Forming in the Process of Work of an APP

Components of wates	Mass fraction, %	Elemental composition, %				
		C	H	O	N	S
Textile fabrics (fabric materials, rags, thick felts)	50	56.1	6.8	32.2	4.8	0.1
Timbers, heat insulators (except for asbestos), suberic materials	20	51	6.1	42.6	0.2	0.1
Paper, board, etc.	10	46.2	6.2	47.1	0.27	0.23
Special footwear (leather, leather substitute)	5	77.9	6.0	15.1	0.3	0.7
Rubber products (special footwear, gloves, etc.)	3	77.9	6.0	15.1	0.3	0.7
Plastic materials (films, bags, and film clothes)	2	67.7	9.3	21.5	1.1	0.4
Moisture	10					
On the average for elements of the wastes*		50.5	5.9	31.0	2.5	0.2

*Content of moisture in material of the wastes 10%.

Burning of Radioactive Wastes. The main, generally recognized thermal method of processing of radioactive wastes is burning them in gas-fired or fuel-oil-fired furnaces. However, the products of these processes — ash, briquettes, salts — do not assure a reliable localization of the radionuclides because of their unsatisfactory characteristics. For example, the ash taken from a plant for burning solid radioactive wastes is unsuitable for direct burial because it represents a dusty dispersed material that is easily leached by water and, therefore, requires an additional treatment — asphalt groating or cementation.

In addition to the burning of radioactive wastes in an open flame, the thermal oxidation of their organic components is widely used. Examples of such processes are the oxidation of organic substances in humid air; the burning of them in a melted salt, a melted glass, a plasma discharge, or a cyclone; their plasma pyrolysis, and so on.

Plasma-Thermal Processing. As was shown in a number of works [2–4], a low-temperature plasma can be used in the technology of processing of radioactive wastes for obtaining their highly stable forms. The main advantages of this method are that it provides a means for the processing of wastes with a large output of a material with the use of equipment having small overall dimensions, the formation of a required gas atmosphere, the simultaneous processing of different radioactive wastes without their preliminary sorting, and the obtaining of high-temperature wastes possessing very high chemical and radiation stability and mechanical strength. The high temperatures of the process (1500–2000^{o}C) provide a large depth of processing of the initial radioactive wastes and an adequate decrease in their amount. Among the wastes stabilized under the action of high temperature, of the most interest are artificial stones representing synthetic analogs of rocks remaining stable during long geological periods. This technology of recovery of wastes can be realized only in plasma furnaces.

Two-Chamber Plasma Furnace for Burning of Radioactive Wastes. The furnace for burning of radioactive wastes, the design of which was developed at the All-Russian Designing and Scientific-Research Institute of Complex Power-Production Engineering (by the data of the Smolensk APP), represents a two-chamber furnace, the diagram of which is shown in Fig. 1. The prototype of this furnace is a furnace operating on the basis of gas and oil burners. In it, burners of total power 300 kW can be used. However, at the Smolensk APP, instead of burners, electric-arc plasma generators of total power 100 kW are used. The burning chamber of the furnace and the reburning chamber are lined on the inside by chamotte and silica bricks. The volume of the burning chamber is 2.0 m^3, and the volume of the reburning chamber is 0.6 m^3. In the process of start run-up of the furnace, its temperature is brought up to 800^{o}C, after which wastes are fed into the burning chamber.

The operation of the furnace begins with its heating by two plasma burning facilities installed in the burning chamber. A burning facility represents an electric-arc plasma generator of the PDS-3 type, enclosed in a special body — a lance cooled with atmospheric air (20.0 m^3/h).

In accordance with the technological design of the furnace being considered, the processing of wastes is performed in two stages: the preliminary burning of the wastes in the burning chamber of the furnace and the subsequent reburning of the products formed in the reburning chamber, where all environmental parameters of the burning should be provided. The reburning at the second stage is provided by an additional (the third) plasma generator installed in the reburning chamber.

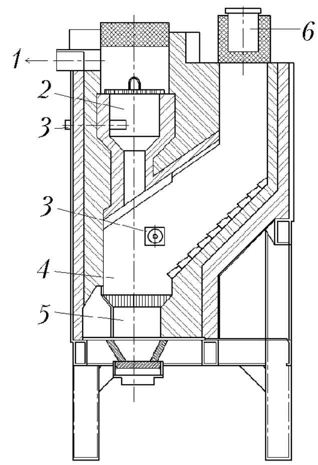

Fig. 1. Diagram of a two-chamber plasma furnace: 1) outlet to the gas-purification system; 2) reburning chamber; 3) plasma generator; 4) burning chamber; 5) means for unloading of the slag; 6) sluice chamber for loading.

TABLE 2. Operating Parameters of Electric-Arc Plasma Generators of Different Powers

Parameters	Power of a generator, kW		
	50	100	150
Efficiency, %	75	75	75
Flow rate of the plasma-forming gas (air), g/sec	3.5	12	15
Enthalpy of the plasma flow, MJ/kg	10.7	6.3	7.5
Mean-mass temperature of the plasma flow, K	5000	3700	4000

In the process of operation of different-design plasma furnaces, including the above-described two-chamber furnace, it is necessary to select the operating parameters for the plasma burning facilities at the stage where the furnace is brought into operation (heating of the furnace to the operating temperature equal to $800^{\circ}C$) and at the stage of its operation in the stationary regime of processing of wastes. In the process of burning of radioactive wastes, the products of incomplete combustion are transported from the burning chamber to the reburning chamber, where, despite the additional heat supplied by the plasma jet of the third plasma generator, the required optimum regime of reburning cannot always be provided. The waste flue gases (WFG) containing a large amount of soot and gummy substances are transferred through the gas conduit to the gas-purification system that does not necessarily provide required the technological purification parameters.

In the literature, different plasma furnaces are described; however, methods of their calculation are practically absent. For the purpose of determining the optimum operating conditions of a two-chamber plasma furnace, we have developed a model of its thermal design for both the regime of heating and the regime of processing of radioactive wastes.

Adaptation of the Methods for Calculating a High-Temperature Technological Plant for a Plasma Furnace. Based on the methods of calculating high-temperature plants, we have developed a method for calculating the thermal parameters of a plasma furnace. In the technology proposed for the plasma-thermal processing of wastes, a PDS-3 electric-arc plasma generator or its modification is used as a burning facility and atmospheric air is used as the plasma-forming gas, the pressure of which at the input to the plasma generator is 0.5 MPa. The characteristics of different-power plasma generators are presented in Table 2.

In the burning chamber of the furnace, wastes are subjected to pyrolysis and their organic mass is burned partially. In this case, the following main chemical reactions proceed in this chamber [5]:

$$2C + O_2 = 2CO + 58.86 \text{ kcal/mole}, \quad C + H_2O = CO + H_2 - 28.38 \text{ kcal/mole},$$

$$CO + H_2O = CO_2 + H_2 + 10.41 \ \text{kcal/mole} .$$

Sulfur, because of its small amount, insignificantly contributes to the thermal balance of the furnace and, therefore, can be disregarded. It may be suggested that the nitrogen contained in the wastes also has no significant influence on the thermal balance of the furnace because it is transformed into the molecular form and is mixed with the nitrogen of the air - the plasma-forming gas. The gas mixture is transferred from the burning chamber of the furnace to the reburning chamber.

The burning regime was simulated by the methods of calculating metallurgy furnaces [6], adopted for plasma furnaces. The amount of air necessary for the complete burning of 1 kg of wastes is determined by the formula [7]

$$V_{1\ \mathrm{kg}} = 0.089\ [(n_\mathrm{C}) + 0.375\ (n_\mathrm{S})] + 0.265\ (n_\mathrm{H}) - 0.033\ (n_\mathrm{O}) .$$

The heat supply to the system is provided by the plasma jet generated by the electric-arc plasma generators and is determined from the relation

$$Q_\mathrm{pl} = \eta N \tau .$$

The loss of heat is due to the heat conduction through the walls of the furnace chamber:

$$Q_\mathrm{w} = \lambda\ (t_\mathrm{g,out} - t_\mathrm{g,in})\ \sqrt{F_\mathrm{in} F_\mathrm{out}} .$$

One of the most important problems associated with the operation of a plasma furnace is the necessity to bring it into operation for an optimum time because the power supplied by the plasma generators is usually limited. It should be noted that, when the operating temperatures of the plasma furnace are attained, the power of these plasma generators becomes sufficient to maintain and intensify the burning of the wastes because additional heat is released in the process of burning of their organic part.

To determine the time of heating of the furnace, we calculated its thermal balance with the use of the method defining the convective regime of operation of furnaces [8]. The amount of heat necessary for heating of a furnace is equal to

$$Q_\mathrm{h.f} = cM\Delta t .$$

The furnace chamber is heated due to the convective heat exchange between the gas flow and the walls of the chamber and by the heat emitted by the torch of the plasma generator. The heat transferred as a result of the convective heat exchange is calculated by the Newton–Rihman law [8]

$$Q_\mathrm{con} = \alpha\ (t_\mathrm{g} - t_\mathrm{w})\ F_\mathrm{out} .$$

The coefficient α of heat transfer in the process of convective heat exchange is determined by the Martinelli formula

$$\frac{\alpha}{c_\mathrm{g} G} = \frac{\sqrt{\xi/2}}{\dfrac{t_\mathrm{w} - t_\mathrm{g}}{t_\mathrm{w} - t_\mathrm{g,c}} \left[\mathrm{Pr} + \ln\ (1 + 5\mathrm{Pr}) + 0.5 f\ (\mathrm{Re};\ \mathrm{Pe})\ \ln \left(\dfrac{\mathrm{Re}}{60} \sqrt{\xi/2} \right) \right]} .$$

The mean-mass temperature of the gas flow is determined by the temperature dependence of the enthalpy. The enthalpy is determined by the formula

$$H = \frac{N}{G} .$$

According to the results of our calculations, the amount of heat necessary to heat of the walls of the burning chamber to 800°C is equal to 5.9 GJ. For this purpose, two plasma burning facilities are used. The plasma generators,

TABLE 3. Results of the Calculation of the Thermal Design of the Burning Chamber of a Plasma Furnace

Parameters	Operating conditions		
	1	2	3
Number of plasma generators	2	2	2
Power of a plasma generator, kW	50	100	150
Efficiency of a plasma generator, %	75	75	75
Flow rate of the plasma-forming gas (air) in the plasma generators, g/sec (nm^3/h)	7 (21)	24 (72)	30 (90)
Flow rate of the air in a lance, g/sec (nm^3/h)	20 (60)	20 (60)	20 (60)
Total flow rate of air, g/sec (nm^3/h)	27 (81)	44 (132)	50 (150)
Total energy supplied, kW	75	150	225
Temperature of the gas at the output of the burning chamber, ^{o}C	870	900	950
Time of heating of the burning chamber, h	53	17	10

the operating parameters of which are presented in Table 2, are enclosed in lances, for cooling of which atmospheric air is additionally supplied (20 nm^3/h). In the burning chamber of the furnace, this air is mixed with the plasma jet. The heat emitted by the plasma torch is equal to

$$Q = 0.5\,(\varepsilon_w + 1)\,C\left[\varepsilon_t\left(\frac{t_t}{100}\right)^4 - \varepsilon_{t,w}\left(\frac{t_w}{100}\right)^4\right].$$

Results of Simulation of the Heating of the Burning Chamber of the Furnace Operating in the Heating Regime. The burning chamber of the furnace is heated by two plasma generators of varied power: 50, 100, and 150 kW. The amount of air supplied into the chamber was also varied. The thermal parameters of the burning chamber were calculated for the following operating conditions:

I. The flow rate of the air supplied into each lance for cooling of the plasma generator is equal to 20 nm^3/h (Table 3).

II. The total flow rate of the air supplied into the burning chamber for cooling of all the technological equipment (the lances of the plasma generators, the peep-holes, the measuring elements) is equal to 170 nm^3/h.

III. The total flow rate of the air supplied into the burning chamber through all the technological holes and the fire bars of the bottom is equal to 470 nm^3/h.

The results of our calculations show that, for the heating of the burning chamber of the furnace and the provision of its operating conditions, it is advantageous to use two plasma generators of power 150 kW each and to supply additional air only into the lances of the burning facilities for cooling of the technological units and members. Under these conditions it will take approximately 7–10 h for heating the furnace to 800–900^{o}C. Our calculations have shown that there is no point in using other regimes of operation because, in them, the time of heating of the furnace exceeds the technologically acceptable norms.

Under the actual conditions of operation of the two-chamber furnace at the Smolensk APP, heated by two plasma burning facilities of total power 100 kW each at a flow rate of the plasma-forming gas of 30 m^3/h and a total amount of the additionally supplied air of up to 170 m^3/h, it has been possible to heat the burning chamber of the furnace only to 300–400^{o}C for 7–8 h of the work, after which wastes began to be fed. Due to the energy released as a result of the combustion of the organic part of the wastes, the temperature in the burning chamber was increased to 800–900^{o}C. These results correlate fairly well with the data of the calculations, according to which the prior heating of the furnace if only to 800^{o}C with the use of two plasma burning facilities of power 50 kW each is impossible for a technologically justified period of time.

The furnace can be run up to the required regime of operation by feeding wastes into the burning chamber, which was realized in practice. In calculating the burning chamber of the furnace operating in the regime of burning of organic radioactive wastes, it is necessary to take into account the calorific value of these wastes. This value is determined by the Mendeleev formula [7], obtained using the calorimetric method:

$$Q_{1\,\text{kg}} = h_\text{C}\,(n_\text{C}) + h_\text{H}\,(n_\text{H}) - h_{\text{H}_2\text{O}}\,(9n_\text{H} - n_{\text{H}_2\text{O}}) - h_{\text{O–S}}\,(n_\text{O} - n_\text{S})\,.$$

In the case where the output of the furnace is equal to 50 kg/h, the electric power supplied to the plasma burning facility is 150 kW, the specific calorific value of the wastes is 20.2 MJ/kg, and the energy released as a result of the burning of the wastes can reach 220 kW. This provides the run-up of the furnace to the required operating conditions. Below are the results of calculations for the furnace being considered, operating in the regime of burning of wastes:

Power of the plasma generator, kW	150
Mass of the bag of the wastes being processed, kg	5
Time of a cycle of processing of a bag with wastes, min	6
Rate of the total air flow, nm^3/h	515
Specific calorific value of the wastes, MJ/kg	20.2
Energy released as a result of the burning of wastes, kW	222.2
Total heat supplied, kW	334.7
Loss of heat through the wall, kW	14.9
Heat removed by the gas from the burning chamber, kW	317.1
Rate of the gas flow at the output from the burning chamber, nm^3/h	548
Temperature of the gas at the output of the burning chamber, ^{o}C	1300

Calculation of the Gas Dynamic and Heat Parameters of the Mixing of a Flue-Gas Flow with a Plasma Jet in the Reburning Chamber. The gas-dynamic parameters of the thermochemical plasma burning of the waste flue gases (WFG) in the reburning chamber were calculated using the model of gas motion, heat transfer, and thermochemical transformations, adapted to the geometry and the temperature regime of the reburning chamber.

In investigating the processes of mixing and heat exchange of isothermic counter jets or flows [9, 10], the ratio between their diameters $R = d_1/d_2$ is used as a determining geometric parameter, and the ratio between their velocities $m = v_1/v_2$ is used as a determining regime parameter.

For nonisothermal mixing of a cold gas jet with a plasma flow, the determining geometric parameter is $R = d_\text{p}/d_\text{g}$. As for the parameter m, in the case of nonisothermal mixing, the high-temperature plasma flow should be replaced by a cold-gas flow identical to it in gas-dynamic parameters, with a temperature equal to the temperature of the cold counter jet having a velocity v_1. This replacement is possible if the replacing cold jet has a kinetic head equal to that of the hot jet, i.e., if the condition $\rho_\text{g} v_\text{g}^2 = \rho_\text{p} v_\text{p}^2$ is fulfilled. It follows herefrom that

$$v_\text{p} = v_\text{g} \sqrt{\frac{\rho_\text{g}}{\rho_\text{p}}}\,.$$

Substitution of the value of v_p into the expression for the parameter m gives

$$m = \frac{v_\text{g}}{v_\text{p}} \sqrt{\frac{\rho_\text{p}}{\rho_\text{g}}}$$

or, passing from the velocity of the gas flow to its rate, we obtain

$$m = \frac{G_\text{p}}{G_\text{g}} (\bar{R})^2 \sqrt{\frac{\rho_\text{g}}{\rho_\text{p}}}\,.$$

To make preliminary estimates of the main operating characteristics of a reburning chamber operating in the counterflow regime, we numerically calculated the zones of collision of the plasma jet with the WFG flow with consideration for the nonisothermality of the counter jets, their initial moments, and the diameters of the cross sections.

It is known that a collision of two counter jets having different initial momenta and diameters of the cross sections leads to the formation of a circulation zone near the source with a large initial momentum, around which a

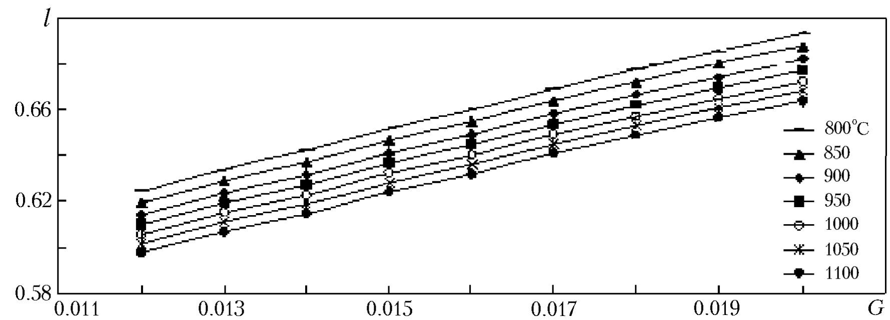

Fig. 2. Depth of penetration of plasma jets into an WFG flow as a function of the flow rate of the plasma-forming gas (the power of a plasma generator is 150 kW and its efficiency is 75%) at different temperatures of the WFG.

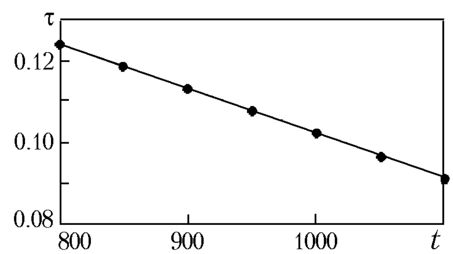

Fig. 3. Time of propagation of the WFG in the reburning chamber as a function of the WFG temperature (the flow rate of the plasma-forming gas is 15 g/sec, the power of a plasma generator is 150 kW, and its efficiency is 75%).

jet with a smaller momentum flows. The length of the back-current zone (or the penetration depth), measured from the source with a larger momentum, can be determined from the relation [11]

$$\frac{l}{L} = \frac{1}{1 + \frac{v_1 d_1}{v_2 d_2}} .$$

The influence of the nonisothermality of the above-indicated jet and flow on their mixing can be approximately estimated from the equality of the dynamic heads of the hot jet and the cold jet simulating this hot jet: $\rho_1 v_1^2 = \rho_2 v_2^2$; this equality allows one to replace the hot jet by the cold one identical to it in gas-dynamic parameters [12].

The above assumption, used in the numerical analysis, was experimentally tested on the plasma plant of [13]. The dependence obtained $l/d = f(v_1/v_2)$ is approximated by the expression

$$\frac{l}{d} = 1.43 \left(\frac{v_1}{v_2}\right)^{0.34} .$$

Other theoretical and experimental data concerning the results of our analysis are absent in the published works. Therefore, in our gas-dynamic calculations of the depth of penetration of a plasma jet into an WFG flow, we used the above-presented formula with the following assumptions:

a) a plasma jet flowing from the nozzle of a plasma generator expands with an angle of operation of 23° (natural expansion angle), and the diameter of its cross section at the center of the reburning chamber is taken as the average diameter;

b) the expansion of the WFG flow was not taken into account because of the large diameter of the channel (380 mm) and the small velocity of this flow (approximately 5 m/sec).

The power of the plasma generator installed in the reburning chamber is equal to 150 kW, the flow rate of the plasma-forming gas is 15 g/sec, the diameter of the WFG counterflow at the output of the burning chamber is

380 mm, and the diameter of the WFG flow in the reburning chamber is 800 m. Some calculation results are presented in Figs. 2 and 3.

Our calculations have shown that the depth of penetration of a plasma jet into a WFG flow changes from 53 to 60 cm when the flow rate of the plasma-forming gas changes from 12 to 20 g/sec. It was established that, with increase in the rate of the WFG flow, the penetration depth of the plasma jet decreases insignificantly. For example, when the flow rate of the waste flue gases increases from 350 to 650 nm^3/h, the penetration depth decreases from 66 to 54 cm for a plasma generator of power 100 kW (the flow rate of the plasma-forming gas is 15 g/sec). If the plasma generator used as a heater in the reburning chamber has a power of 150 kW, the depth of penetration of the plasma jet (with a flow rate of 15 g/sec) into the WFG flow with a temperature of 950^{o}C increases from 56 to 60 cm. This allows the conclusion that it is best to use a plasma burning facility of power 150 kW in the reburning chamber.

Conclusions. One of the most promising and universal technologies of processing of radioactive wastes of medium and low activity is their burning in plasma furnaces having significant advantages over the fuel furnaces. We have considered one variant of realization of this technology in a two-chamber plasma furnace. For determining the optimum parameters of operation of this furnace, a method of calculating its thermal design has been developed. Our calculations have shown that it takes the operation of two plasma generators of power 150 kW each for approximately 10 h to heat the indicated furnace to a working temperature. A plasma generator of power 150 kW should be installed in the reburning chamber to completely burn the incomplete-combustion products coming out from the burning chamber. In this case, the zone of penetration of a plasma jet into the WFG flow reaches 55–65 cm, which is favorable to their optimum mixing. The results of the present work were used in the reconstruction of the complex for processing solid radioactive wastes at the Smolensk APP.

NOTATION

C = 5.67 W/(m^2·K^4), Stefan–Boltzmann coefficient; c, specific heat capacity, J/(kg·K); d, diameter, m; F, area, m^2; G, rate of a gas flow, g/sec; H, enthalpy of the gas, J/kg; h_C = 340.2 kJ/kg, empirical value of the specific heat of a carbon formation; h_H, 1260 kJ/kg, the same for hydrogen; h_{H_2O} = 25.2 kJ/kg, empirical value of the specific absorption of heat for evaporation of the chemical water as a combustion product; $h_{O\text{–}S}$ = 109.2 kJ/kg, empirical value of the specific heat of formation of SO_2; L, distance between the sources of the counter jets, m; l, penetration depth, m; M, mass, kg; m, relation between the velocities of the jets; N, power, W; n, mass fraction of an element in a material, fractions; Pe, Peclet criterion; Pr, Prandtl criterion; Q, heat, J; R, determining geometric parameter; Re, Reynolds criterion; t, temperature, ^{o}C; V, volume, m^3; v, velocity, m/sec; α, coefficient of heat transfer in the convective heat exchange; ε, degree of blackness; η, efficiency of a plasma generator; λ, heat-conductivity coefficient of the material, W/(m·K); ξ, coefficient of friction; ρ, density, kg/m^3; τ, times of operation of a plasma generator, sec. Subscripts: 1 and 2, counter jets of large and small diameters respectively; in and out, inside and outside; g, gas; con, convection; h.f, heating of furnace; p, plasma; pl, plasma generator; w, wall; t, torch; c, at the center.

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