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PLASMA-THERMAL PROCESSING AND INCINERATION OF WASTES IN A SHAFT INCINERATOR WITH A COMBUSTIBLE FILTERING MATERIAL

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The authors report the basic technological principles and the special features of a method of combined plasma-thermal processing and incineration of harmful wastes in a shaft incinerator under a layer of the charge of such a well-filtering and well-combustible material as wood sawdust, which absorbs up to 99% of the aerosols of waste gases by fixing and concentrating them in the ash. A calculated-analytical estimate of the filtration properties of wood sawdust is obtained as a function of its dispersity, the thickness of the charge layer, and the filtration rate of the waste gases. Determination is made of the optimum design relations and the parameters of charging of a filtering material under different conditions of processing of wastes, including moistening and impregnation of wood sawdust by an aqueous solution of sorbents to absorb harmful metals. The calculated results are compared and demonstrate consistency with the data on the filtration properties of wood sawdust in other technologies, including thermal processing of radioactive wastes in a similar shaft incinerator.

The problem of gas effluents and gas cleaning in incineration and thermal processing of hazardous wastes is fundamental and to a considerable extent restricts the applicability and efficiency of this technology. Thus, for instance, ordinary garbage combustion in conventional waste-heat boilers gives up to 30–40% of the aerosol removal of volatile ash, the catching of which requires powerful gas-cleaning systems to meet the environmental standards now in force for gas effluents into the atmosphere. In the case of incineration of radioactive wastes, these standards become substantially more stringent and expenditures on such gas cleaning exceed, as a rule, those on the processing itself [1, 2].

In this connection, at the Academic Scientific Complex "Heat and Mass Transfer Institute" (ASC HMTI) (Belarus, Minsk) a shaft-filtration method of plasma-thermal processing and incineration of hazardous wastes, including low-radioactive ones is being developed that is implemented in a shaft incinerator under a charge layer of such a well-filtering and well-combustible material as fine wood sawdust, through which waste flue gases are filtered and are purified [3-6]. As the wood sawdust is charged, it burns out together with the wastes, thus fixing (calcining) and concentrating the absorbed aerosols in its ash. The filtration of the gases in such a layer is supplemented to a considerable degree by their cooling and the absorption by condensation of a number of hazardous evaporated wastes, including metals and radionuclides. In this case, the known filtration and sorption properties of wood sawdust that were employed in similar but individual technologies of gas cleaning and radioactive decontamination in the 60s are used in combination. In particular, we can mention the experience of direct use of wood sawdust for the filtration of gases from dust [7], including the case of waste gases in thermal processing and gasification of wood [8], where the efficiency of this gas cleaning attained 99.9%. As applied to the water absorption of strontium-90 radionuclides, the experience of the impregnation and activation of sawdust by solutions of magnesium, potassium, and sodium salts is reported in [9]. For the sorption of the vapor of such harmful metals as cadmium, lead, etc. sawdust can be activated and impregnated [10, 11] with an aqueous solution of alumosilicate and bauxite sorbents, which are also efficient in the apsorption, mineralizing, and encapsulation in a certain way of volatile compounds of these metals in ash particles.

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Current studies of the structural and elemental composition of the ash in such processes of multicomponent incineration of wood organics with impurities of those metals and silicates [12] convincingly confirm in detail these properties and possibilities. Thus, this method of processing of wastes allows tenfold reductions in the removal of harmful aerosols and evaporated wastes, thus increasing the efficiency and service life of available gas-cleaning systems, and at the same time, providing simplification and reduction of the expenses on newly designed systems.

A direct example and an analog of this problem is the experience of thermal processing of low-active radioactive wastes in a shaft incinerator at the Specialized Scientific and Production Association "Rodon" [13], where up to 85–90% of finely divided wood was charged into the volume of the wastes, through which waste gases were filtered from bottom to top. Here, a high technological effect of this charge mixture relative to the absorption of radionuclides was noted; it is characterized by the removal (breakthrough) of only 1–2% of the total initial activity of the wastes at the outlet of the flue gases. Since the radioactivity of the waste gases in this process is determined, as evaluated by Dmitriev et al. [13], for 99% of the aerosol phase of the radionuclides, this testifies to the high filtration capability of this charge composition. Moreover, with a decrease to 350–300°C in the temperature of the exhaust gases of the incinerator, the selective effect of the absorption of volatile cesium-137 radionuclides was noted, the relative breakthrough of whose activity also decreased to the level of 1–1.5% of the initial one. Provided its sufficiently complete sublimation in the incinerator, where the temperature reached 1500°C (with an intrinsic boiling point of 950°C), this undeniably can and must be related to the condensation effect of the absorption of the activity of cesium-137 as the most volatile component at the indicated temperature.

Technology of Processing of Wastes with a Filtering Material. The principle and the distinguishing feature of the technology developed at the ASC HMTI consist of simultaneous incineration of wastes in a shaft incinerator with a certain ratio between the wastes and the fill of a filtering material of wood sawdust at the top in each cycle of charging. As a result, a multilayer sandwich structure of this charge is formed with respect to the height of the incinerator shaft (see Fig. 1), which improves somewhat the uniformity of the gas-flow filtration, prevents shaft seizure, and also makes it possible to prescribe the required filtering properties of the upper sawdust layer independently of the structure and density of the charge of the wastes themselves. As a consequence, a filter bed is ensured in the incinerator shaft at the top, the height of which H is determined as a function of the prescribed extent filtering degree E according to [4] as

$$E = 1 - \frac{C(H)}{C_0} = 1 - \exp\left(-\frac{H}{L_e}\right), \tag{1}$$

$$L_e \cong 3.3\,\mu R^2 \left[\frac{kT}{\pi \vartheta r}\left(\frac{1-\varepsilon}{\varepsilon}\right)^2 + r^2 \rho \vartheta\right]^{-1}. \tag{2}$$

Formulas (1) and (2) are obtained using the traditional molecular-kinetic model of double, diffusional, and inertial transfer of monodisperse aerosols entrained by a gas flow in curvilinear pores-channels of a packed filter bed [14], in the context of which in this case we have employed the method of independent solution and summation of the corresponding equations of transfer. The exponential dependence obtained is typical of many processes of transfer in absorbing media and, in particular, is similar to the formula of filtration and absorption of aerosols in fine-fibered filters [15].

By analogy with [13] and other similar technologies, incineration of wastes also proceeds in two stages with a small volume and lack of air in the incinerator burner at the bottom with α = 0.3–0.4 and with the subsequent complete afterburning of gases in a separate cyclone chamber at the incinerator outlet from top, as is shown in Fig. 1. In this regime, only the carbon part of the wastes and of the filtering material that remains after their pyrolysis in the shaft burns out. Incineration of the wastes in the incinerator burner is carried out at 800–850°C, the exhaust flue gases are cooled over the charged-layer height in the shaft to 250–300°C or lower,

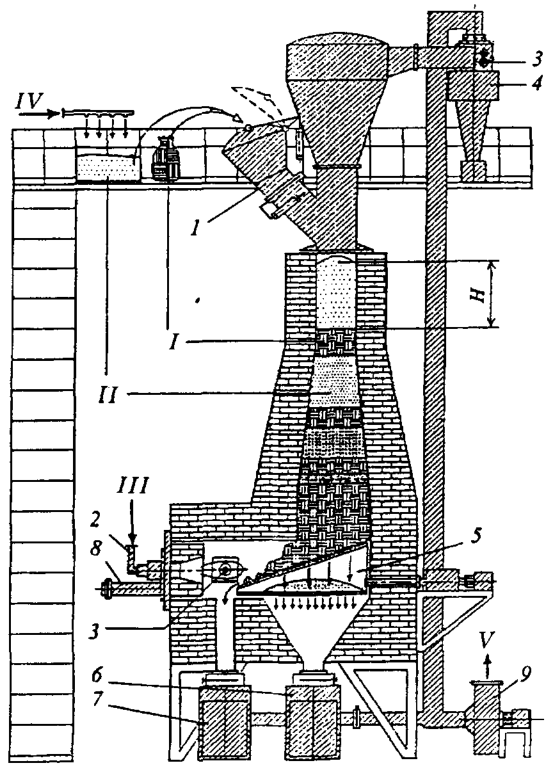

Fig. 1. Schematic of a shaft-filtration incinerator for plasma-thermal processing and incineration of harmful wastes with a combustible and filtering material: 1) bunker for charging of solid wastes; 2) nozzles of evaporation of liquid wastes; 3) plasma-air burners (plasmatrons); 4) section of gas afterburning; 5) reciprocating grate; 6, 7) chambers of discharging of ash and ash residues of processed wastes, respectively; 8) inspection hole; 9) exhaust fan; *I*) solid wastes; *II*) filtering material; *III*) liquid wastes; *IV*) sorbents of toxic metals; *V*) waste gases used for decontamination.

thus supplementing filtration by the effect of condensation absorption of a number of volatile components of the wastes and their radionuclides that can be sublimated at this temperature of the incinerator. Apparently, at the indicated temperature of the waste gases, the resinous products of pyrolysis of the sawdust itself are also condensed and increase the efficiency of their filtration by coagulating fine aerosols into coarser ones.

The incinerator is heated by electric-arc, air-plasma burners (plasmatrons) that are developed at the ASC HMTI and provide the required temperature for the incineration of a variety of wastes with air lack, as is indicated above. In this case, the method of plasma heating of the incinerator is justified and is based on the high enthalpy characteristic of the plasmatrons, which allows the processing of wastes with a small volume and a low filtration rate of the exhaust gases. The same plasma equipment of the afterburner section allows the afterburning at 1500–2000°C and thermal neutralization of various toxic impurities constituting the exhaust gases. In addition to the plasmatrons, the incinerator burner is equipped with conventional sprayers of liquid fuel, which, if necessary, allows the incineration and processing of other liquid wastes, including noncombustible ones, for instance, spent aqueous-deactivation solutions contaminated with the impurities of radioactive sand, soil, etc. In this case, the process involves high-temperature evaporation of this liquid at 800–850°C followed by the absorption of the formed radioactive aerosols in the shaft layer of the charge of the same filtering material. As in the case of solid-fuel wastes, the material also burns out; the absorbed aerosols are calcined and are concentrated in its ash.

The wastes and the filtering material in the furnace burner are incinerated on a reciprocating grate that allows the charge layer to move from above and the ash to fall into the chamber from the bottom and from the side of the incinerator, as is shown in Fig. 1. Noncombustible residues are discharged down the grate and enter the second discharge chamber arranged in the same way. Each chamber has an airtight barrel-container of ash placed on a carriage that, after being filled with ash, is replaced by another in a certain way. Aspiration safety of such ash discharging is ensured by active ventilation of these chambers under the total-evacuation conditions of the exhaust fan of the incinerator. Similarly, the charging bunker on the service platform of the incinerator is ventilated from above. This system provides for further conditioning of the ash to be buried by cementing or melting-vitrifying with a glass-forming mixture, which is already governed by the technological and technical-economic factors.

Ratio between the Charge of Wastes and the Filtering Material. Since the present method leads to the formation of an additional amount of the ash of the filtering material to be buried, it is necessary to solve the problem of its sufficient amount required at the corresponding ratio between its charge and wastes. Physically, the problem is defined as follows. This is such a ratio at which the volume and the filtration rate of the exhaust gases as products of their simultaneous combustion on the basis of the flow area of the incinerator shaft correspond to the known optimum value $\vartheta_o = 0.1–0.15$ m/sec that is typical of the majority of granular filled filters, including wood-sawdust ones [7, 8].

In the main regime of processing of solid-fuel radioactive wastes in the form of cellulose-paper and package wastes and wastes of used-up protective cloths and footwear as well as textile cartridges and packing of different filters, which are characterized by, approximately, the same combustible composition as the wood sawdust has, this problem is solved by the ordinary system of equations and definitions of the material-volume balance of this process:

$$V = V_d + V' + V'' , \tag{3}$$

$$V_d = (G_1 + G_2)\,\alpha V_0 , \tag{4}$$

$$V' = G_2 \varphi v' , \tag{5}$$

$$V'' = G_2 w v'' , \tag{6}$$

$$V = S\vartheta , \tag{7}$$

from which the following ratio between the charge of a filtering material and wastes is obtained:

$$m_l = \frac{G_2}{G_1} = \left[\frac{\vartheta - (\varphi v' + w v'')\, g_{2S}}{g_{2S}\alpha V_0} - 1 \right]^{-1} , \tag{8}$$

where the parameters α and V_0 are equally related to the incineration of the wastes and the filtering material of wood sawdust, while $g_{2S} = G_2/S$ is the index of the specific intensity of charging of the latter in the cross section of the incinerator shaft, which in this case is one of the main characteristics of the process under consideration.

An example and an analog of such an index is the well-known characteristic of the already mentioned and approximately the same shaft-layer pyrolytic process of wood carburetion [8], the intensity of the processing of which in the form of a dense bulk layer of chips attains g_{2S} = 200–250 kg/(m^2·h). In our case, with allowance for, approximately, a threefold to fourfold lower bulk density of wood sawdust, this value correspondingly decreases and is g_{2S} = 70–80 kg/(m^2·h).

The optimum filtration rate ϑ_o must also be corrected; this quantity, according to the data of [7, 8], is given at normal temperature t_0 = 20°C. In our case, in the form of a complex correction for an increase in the volume as well as for a decrease in the density and viscosity of outgoing gases at the temperature t_{out} = 250–300°C the following known [16, 17] relation holds for the hydrodynamics of a disperse system of particles of a filter bed and aerosols:

$$\vartheta = \vartheta_o \left(\frac{T_{out}}{T_0}\right)^{0.5} . \tag{9}$$

The second regime involves processing of radioactive wastes in the form of various polymers and plastics of the type of polyvinylchloride, and also of other compositions of saturated and heavy hydrocarbons such as bitumen and asphalt, which are not subjected to such pyrolysis as wood. In this case, the processing of such wastes is carried out in the regime of their complete incineration with a certain excess air $\alpha_1 > 1$, the rest of which provides the pyrolysis and incineration of the filtering material with α_2 = 0.3–0.4. Analytically, this can be expressed and determined in the form of the following equations:

$$G_1 V_{01} (\alpha_1 - 1) = G_2 V_{02} \alpha_2 , \tag{10}$$

$$\alpha_1 = 1 + \alpha_2 m \frac{V_{02}}{V_{01}} . \tag{11}$$

In this case, with neglect of the natural low humidity of the indicated wastes, the initial system of equations (3)-(7) is transformed for the volume of dry gases to the form

$$V_d = G_1 \alpha_1 V_{01} + G_2 \alpha_2 V_{02} \tag{12}$$

and with account for (11) it is solved for m in the following way (the other equations of the bulk composition of gases remain):

$$m_{II} = \frac{G_2}{G_1} = \frac{V_{01}}{\alpha_2 V_{02}} \left[\frac{\vartheta - (\varphi v' + w v'')\, g_{2S}}{g_{2S} \alpha_2 V_{02}} - 2 \right]^{-1} . \tag{13}$$

The third regime is concerned with spraying and evaporation of liquid radioactive wastes, for instance, of spent aqueous deactivation solutions, whose evaporated aerosol is also filtered in a sawdust layer. In this case, the temperature and the thermal balance of the incinerator shaft at the level of 800–850°C are maintained by the plasmatrons with general feed of air through them and the spray nozzles also in the limits of the pyrolysis coefficient of the filtering material α_2 = 0.3–0.4. Here, the initial system (3)-(7) is transformed for the volume of dry gases and moisture and is solved in the following way (with other equations also remaining in it):

$$V_d = G_2 \alpha_2 V_{02} , \tag{14}$$

$$V'' = G_1 v'' + G_2 w v'' , \tag{15}$$

$$m_{III} = \frac{v''}{\alpha_2 V_{02}} \left[\frac{\vartheta - (\varphi v' + w v'')}{g_{2S} \alpha_2 V_{02}} - 1 \right]^{-1} . \tag{16}$$

As a result, it becomes possible to calculate correctly and most optimally the required shaft cross section and overall dimensions of the incinerator so that with a prescribed charge of the wastes the filling of wood sawdust provides the necessary height and efficiency of the filter bed according to (1)-(2). In the regime of their alternate charging this is simply determined as

$$S=\frac{G_2\tau}{\rho_2 H}=\frac{m_{I\text{-}III}G_1\tau}{\rho_2 H}. \qquad (17)$$

Finally, of separate interest is the problem of the possibility of charging and processing of a maximum wet filtering material in the looseness limit of wood sawdust with a humidity up to $w_{\max}$ = 50%, in particular, with their activation by impregnation with the aqueous solution of sorbents for absorption of harmful metals. In this case, use can be made of the known data on the shaft method of drying of dispersed materials in a flow of flue gases [18], the volume intensity of which based on the moisture content in relation to the temperature regime of drying is characterized in the limits W_V = 20–50 kg/(m^3·h). Having determined the volume of filling and the content of the evaporated moisture of the filtering material in the form

$$V_2=HS, \qquad (18)$$

$$W=G_2 w_{\max}, \qquad (19)$$

we arrive at the following expression for its maximum permissible humidity:

$$w_{\max}=\frac{HW_V}{g_{2S}}. \qquad (20)$$

Comparative Analysis of the Results. The expense of the technology under consideration somewhat restricts the possibilities of its full-scale implementation and the conducting of such pilot investigations that could provide direct evaluation of the above analytical representations and calculations. Nevertheless, the references cited in the present work allow this evaluation by employing experimental information about other technologies. For instance, for the mean morphological composition of wood sawdust with the total content of light volatile components of wood (alcohols, acids, formaldehydes, etc.), e.g., φ = 30%, humidity w = 30% and also for the remaining known and indicated parameters of the process in the limits ϑ_0 = 0.1–0.15 m/sec, α_2 = 0.3–0.4, V_{01} = 10–12 m^3/kg, V_{02} = 2.5–3.0 m^3/kg, v' = 1.5–2.0 m^3/kg, v'' = 1.7 m^3/kg, and g_{2S} = 60–80 kg/(m^2·h) for each of the above-indicated regimes of processing with a temperature of the outgoing gases of t_{out} = 250–300°C in accordance with (8)–(10) and (16) we can determine approximately the following calculated ratios of the charging of wastes and the filtering material of sawdust (in the parentheses is the percentage of sawdust per total mass of the charge):

m_I = 0.3–0.5 (25–35%);
m_{II} = 3.0–4.0 (75–85%);
m_{III} = 0.5–0.7 (35–40%).

Turning to the experimental data obtained by the "Radon" Scientific and Production Association [13] on shaft processing of radioactive wastes with a content of 85–90% of wood reduced in size (humidity of, approximately, 30%, which contained also up to 10% of noncombustible construction refuse and 5% of polymers), we can see that they directly confirm this calculation for the regime of the processing of polymers at m_{II} = 3.0–4.0 with a content of the filtering material of sawdust up to 85%. Here, for the indicated temperature of the waste gases the following data can serve as an example of the calculated charging of the filtering material of wood sawdust by (1) and (2):

fraction of aerosol particles $2r$, μm	5–10
fraction of wood sawdust $2R$, mm	3–5

porosity of the filter bed ε	0.8–0.9
filtration rate of the gases ϑ, m/sec	0.1–0.15
prescribed efficiency of filtration E, %	99.0
required height of the filter bed H, m	0.5–0.7.

The calculation results are quite consistent with the experimental data on the use of wood sawdust for the filtration and cleaning of almost the same waste gases in thermal processing and gasification of wood that were extensively used earlier [7]. In particular, at a calculated velocity of the gas flow of $\vartheta = 0.1$ m/sec the concentration of resinous-soot aerosols in it at the level of 70–80 g/m^3 after filtration in a sawdust layer with height $H = 0.8$ m decreased to 50–70 mg/m^3, which characterized the efficiency of gas cleaning of about E = 99.9%. In this case, the gas temperature at the outlet did not exceed 100°C and, apparently, this higher result of filtration (by an order of magnitude) was even to a greater degree attributed to the effect of condensation absorption of aerosols when they are wetted and are coagulated in a more saturated medium not only of the resinous but also of other volatile components of wood that are condensed at this lower temperature.

Finally, using a filter bed with height $H = 0.7$ m as an example, from the data of [18] we can evaluate and show that this height of the filling meets the conditions of shaft drying of the maximum moist sawdust when it can be purposefully impregnated with an aqueous solution of a number of sorbents for the absorption and mineralization of evaporated harmful metals [10, 11]. If the regime of wood-sawdust drying in a flow of flue gases outgoing directly from the incinerator burner is characterized as the highest-temperature one under these conditions and the indicated volume intensity of this process is evaluated by the corresponding maximum $W_V = 50$ kg/(m^3·h), then with the specific charging of the wood sawdust in the limits g_{2S} = 60–80 kg/(m^2·h), according to (20) we obtain, on the average, $w_{\max}$ = 50%. Thus, the analytical results of this investigation provide quite real and promising premises for further development, improvement, and successful implementation of the suggested method.

NOTATION

τ, G_1, G_2, and m, cyclic recurrence and capacity of the incinerator relative to the charging of the wastes and the filtering material (wood sawdust) and their ratio in the charge, respectively; w and φ, humidity and total percentage of light volatile wood components not condensing at the temperature of the waste gases (wood alcohols, ethers, formaldehydes, etc.); v' and v'', specific volume of the indicated evaporated components and steam (at normal pressure); V_d, V', V'', and V, volume of the dry flue gases, the volatile components, the evaporated moisture, and their total value, respectively; α, coefficient of excess air in the incinerator burner; V_0, theoretical (stoichiometric) air volume for normal incineration of 1 kg of the wastes and the material; S, cross-sectional area of the incinerator shaft; g_{2S}, specific load of the cross section of the incinerator shaft with respect to the filtering material of wood sawdust; W_V , volume intensity of their drying in the incinerator shaft; T, ϑ, and μ, temperature, filtration rate, and dynamic viscosity of the waste flue gases, respectively; r and R, radius of the aerosol particles and the filtering material (wood sawdust); ρ, density of the aerosol particles of the ash; C_0 and C, their initial and final concentration; ε, ρ_2, and H, porosity, bulk density, and height of the filter bed of wood sawdust; L_e, characteristic height of this bed, at which the concentration of the aerosols decreases by e = 2.7182... times; k, Boltzmann constant. Subscripts and superscripts: 1, wastes; 2, filtering material; out, outgoing gases; S and V, area of the flow section and shaft volume; 0, at a temperature of 20°C; $'$ and $''$, volatile components and humidity of wood sawdust; d, dry flue gases; max, maximum value; o, optimum value; *I-III*, regimes of processing.

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