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THERMAL PROCESSING OF WASTES IN A SHAFT INCINERATOR WITH A PLASMA BLAST AND A COMBUSTIBLE FILTERING MATERIAL: ANALYSIS OF THE ENERGY CONSUMPTION AND VARIANTS

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As a continuation of previous publications, the authors report results of analytical substantiation and evaluation of energy consumption for different versions of thermal processing, incineration, and evaporation of a wide range of toxic and radioactive wastes in a shaft incinerator with plasma air blast beneath a layer of a charge of filtering and combustible material such as wood sawdust, which absorbs up to 98–99% of the aerosols of waste gases and fixes the aerosols in the ash. The volume and specific energy consumption of the plasma blast and also conditions and possibilities for eliminating it due to the intrinsic heat release of the wastes and wood sawdust by means of this method are determined. The expediency of incineration and vitrification of the ash residue of radioactive wastes separately in a small-volume melting crucible is shown, which allows a no less than twofold decrease in the total energy consumption as compared to the combined version of such processing.

Existing conventional methods and technologies for combustion of garbage and industrial wastes in incinerators and waste-heat boilers [1–3] are characterized by high (30–40%) aerosol removal of ash to a gas-cleaning system and for this reason they are simply inapplicable for such processing and elimination of hazardous, toxic, and radioactive wastes, for which the requirements, expenditures, and conditions of reliability for cleaning of gaseous wastes substantially increase [4]. The most up-to-date and perfect pyrolitic methods of combustion and gasification of such wastes at high temperatures in special plasma-shaft incinerators and pyrolitic reactors [5] are distinguished by a comparatively small output of their gaseous wastes; however they need high specific consumption of heat and electrical energy, including substantial capital outlays for the equipment itself.

In this connection, at the Academic Scientific Complex "Heat and Mass Transfer Institute" (ASC HMTI), National Academy of Sciences of Belarus (Minsk), a shaft incinerator and a technology have been developed for more economical plasma-thermal processing of a wide range of hazardous wastes, among which are biological, halogen-containing, and radioactive wastes with low and moderate activity. The developed technology includes evaporation of liquid and noncombustible wastes of similar type, in which aerosol outbursts of gaseous wastes are filtered in a course of processing and, as compared to the above, decrease to the level of just 1–2% [6, 7]. In brief, this shaft-filtration technology consists in charging and processing of wastes in the shaft incinerator (Fig. 1) in combination with fine wood sawdust, which filters waste gases, absorbs hazardous aerosols, and in the course of the shaft process burns out together with the wastes, fixing and concentrating them in the ash to be buried. This method implements in combination both the combustion and filtration properties of wood sawdust, which was rather widely employed earlier in the simplest bulk

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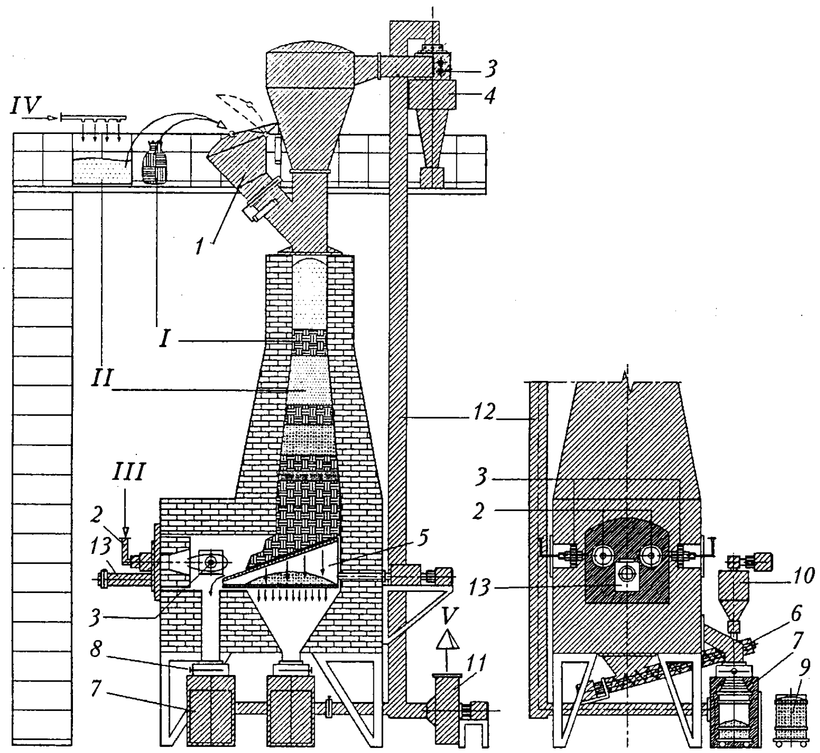

Fig. 1. Schematic of a shaft-filtration incinerator [6, 7] for plasma-thermal processing of toxic, solid, and liquid radioactive wastes (with plasma blast of air and a combustible filtering material of wood sawdust): 1) charging bunker; 2) spray nozzles; 3) plasmatrons; 4) afterburning chamber; 5) reciprocating grate; 6) ash discharge screw conveyer; 7) ash containerization chambers; 8) gates; 9) ash container; 10) position of the cement batcher; 11) exhaust fan, 12) system for rarefaction of charging-discharging; 13) inspection hole; I) solid wastes; II) filtering material; III) liquid wastes; IV) sorbents of hazardous metals; V) waste gases to be decontaminated.

filters [8], including the cases of gas cleaning in thermal processing of the wood itself [9], where the efficiency of the wood sawdust was characterized by the absorption of more than 99% of the initial aerosols. Activation and impregnation of sawdust with an aqueous solution of known aluminosilicate and bauxite sorbents makes it possible to implement these properties even more efficiently and selectively for absorption of a number of hazardous metals [10, 11].

Plasma Blast of the Incinerator and Filtration of Waste Gases. Combustion of wastes in the furnace of this shaft-filtration incinerator is accomplished with air deficiency within the limits of the stoichiometric coefficient α = 0.3–0.5 and a minimum temperature needed for this of 800–850^{o}C, which is preceded by drying and pyrolysis of the wastes in the shaft. Thus, only the pyrolysis-carbon residue of wastes and sawdust is incinerated in the furnace, while the waste gases as the products of their incomplete combustion and pyrolysis burn out in an individual cyclone chamber at the shaft outlet. The shortage of heat released in the furnace in incineration of moist, biological, and other poorly combustible wastes is made up for by a situation under which 10–20% of the air, depending on the humidity of the wastes, is fed in the form of the plasma blast of the process by plasma electric-arc burner-plasmatrons. For an intrinsic temperature of the air plasma of 5000–6000 K this provides the required temperature of the furnace within wide limits of the moisture content and combustion properties of different kinds of wastes up to evaporation of aqueous and noncombustible solution-suspensions of radioactive wastes. In the latter case, the plasma blast of air is increased to 50–70% and the furnace temperature is maintained at the same level of 800–850°C, which makes it possible to charge and burn up the filtering material of sawdust for absorption of evaporated aerosols in the same manner as in the mode of processing other solid combustible wastes.

Under these conditions, with an appropriate choice of the shaft cross section and with a certain wastes-to-sawdust charging ratio in accordance with [7] the calculated rate of filtration of the waste gases and evaporations is 0.1–0.2 m/sec, which is known as an optimum for the bulk filters indicated above, at which their operation is most efficient. In this way, the plasma blast and the incinerator heating by burner-plasmatrons make it possible to minimize the volume of the waste gases and to provide the indicated optimum conditions of their filtration in the whole range of kinds and modes of processing of wastes. Otherwise, in particular, with the use of ordinary gas- or liquid-fuel burners the products of combustion of the fuel itself increase this volume by a factor of 3–4 or more, which leads to substantial hydraulic resistance and nonunifom filtration of gases in the charge layer, thus decreasing and violating the efficiency of the method as a whole.

If the thermodynamic state of the plasma air is considered to be equilibrium for the indicated temperature while the thermal power of the plasma blast is determined from its flow rate and the mass-mean temperature of the plasma [12]

$$Q_{\text{pl}} = G_{\text{pl}}\bar{c}_p t_{\text{pl}} = V_{0(\text{pl})}\, \rho_0 \bar{c}_p t_{\text{pl}} \,, \tag{1}$$

$$V_{0(\text{pl})} = \psi_{\text{pl}}\, V_{0(\text{w,fil.m})} \,, \tag{2}$$

$$V_{0(\text{w,fil.m})} = (G_{\text{w}} + G_{\text{fil.m}})\, v_{0(\text{w,fil.m})}\, \alpha \,, \tag{3}$$

and the heat release and the additional volume of the combustion products of the fuel, including the volume of the gaseous products of pyrolysis of the wastes and sawdust themselves, are determined in the conventional way

$$Q_{\text{f}} = G_{\text{f}} Q^{\text{pr}}_{\text{low(f)}} \,, \tag{4}$$

$$V_{\text{com(f)}} \approx V_{0(\text{f})} = G_{\text{f}} v_{0(\text{f})} \,, \tag{5}$$

$$V_{\text{pyr(w,fil.m)}} \approx V_{0(\text{w,fil.m})} \,, \tag{6}$$

then provided that $Q_{\text{pl}} = Q_{\text{f}}$ the above comparative estimate of a decrease in these volumes in the case of plasma blast is determined from (1)–(6) by the following analytical expression:

$$\frac{V_{\text{out 2}}}{V_{\text{out 1}}} = \frac{V_{\text{pyr(w,fil.m)}} + V_{\text{com(f)}}}{V_{\text{pyr(w,fil.m)}}} = 1 + \frac{V_{\text{com(f)}}}{V_{\text{pyr(w,fil.m)}}} = 1 + \psi_{\text{pl}} \frac{v_{0(\text{f})}\, \rho_0 \bar{c}_p t_{\text{pl}}}{Q^{\text{pr}}_{\text{low(f)}}} \,, \tag{7}$$

where $V_{\text{out 1,2}}$ are the volumes of the waste gases in plasma blasting of air by plasmatrons and in ordinary heating of the furnace by fuel burners, $V_{\text{com(f)}}$ is the volume of the products of fuel combustion, $V_{\text{pyr(w,fil.m)}}$ is the volume of the products of pyrolysis of the wastes and the filtering material, $V_{0(\text{w,fil.m})}$ is the volume of the total supply of air to the furnace for their processing, $V_{0(\text{pl})}$ is the volume of the plasma blast of air, and Ψ_{pl} is the relative volume of the plasma blast as part of the total supply of air.

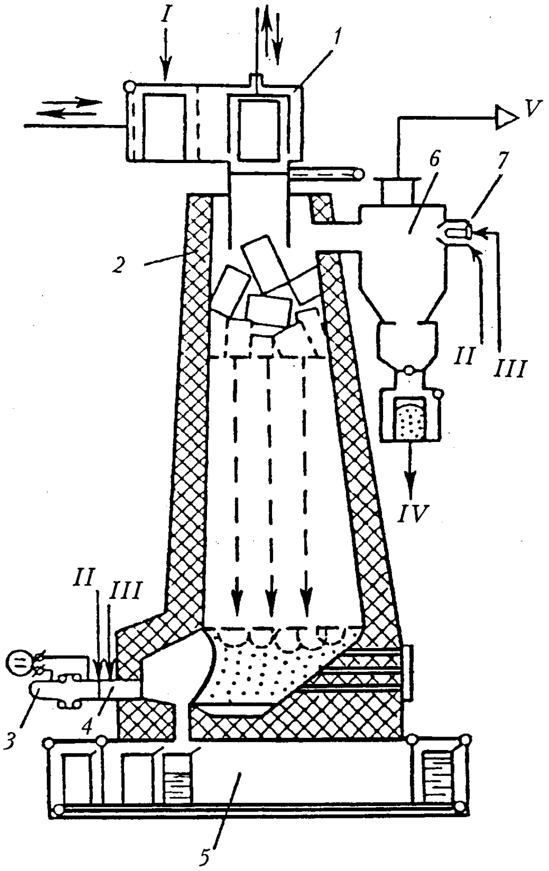

Fig. 2. Schematic of a plasma shaft-melting incinerator [16, 17] for thermal processing and vitrification of radioactive wastes (with plasma-fuel heating): 1) sluice chamber of charging; 2) incinerator shaft; 3) plasmatrons; 4) fuel nozzles; 5) chamber for melt pouring and containerization; 6) chamber for afterburning of the waste gases; 7) fuel injector for afterburning; I) solid wastes; II) compressed air; III) liquid fuel; IV) ash removal; V) waste gases to be decontaminated.

Moreover, plasma blast is intended for afterburning of waste gases on their leaving the shaft (see Fig. 1), where the temperature of such plasma afterburning is increased, if necessary, to 1500–2000^{o}C, thus solving the problem of thermal neutralization of hazardous gases in processing of toxic and halogen-containing wastes [13–15].

Combustion and Vitrification of Radioactive Wastes. Plasma burner-plasmatrons allow one in the same way to increase the furnace temperature, which is implemented and efficiently used for afterburning and vitrification of radioactive wastes with low and moderate activity in a similar plasma-shaft incinerator [16, 17]. With such processing the ash radionuclide residue of radioactive wastes "dissolves" in a glass-mass melt and in this form it is most safe for burial since it is practically not subjected to such a main factor of penetration of radionuclides into water and soil as leaching out. For this purpose, mineral components of the glass-forming burden are added to the waste charge and the furnace of the incinerator is made and lined in the form of a melt bath at a temperature of 1500–1600^{o}C, as is done in similar metallurgical shaft and blast furnaces (Fig. 2). To create the required carbon-reduction atmosphere, the air deficiency in the furnace is also maintained at the level of the pyrolytic coefficient $\alpha = 0.3–0.5$, and up to 85–90% "dry" crushed wood (with a humidity of up to 30%) is added, as the fuel component, to the shaft charge, which imparts to it efficient filtration properties for absorption of radionuclide aerosols.

The possibility of decreasing the energy consumption in such processing of wastes appears in technological separation of the processes of their combustion and vitrification, especially if we pay attention to the fact that the initial volume of the shaft for charging the wastes and all subsequent overall dimensions of the incinerator substantially exceed the final volume of their ash residue. Whereas in metallurgical furnaces the mass and volume of the shaft charge are quite comparable with the melt output, in the present case the ash volume of the wastes after combustion it reduced by approximately a factor of 40–50. Moreover, just as in all similar incinerators, the flow cross section of the shaft is made even wider downward to eliminate crown formation and hanging-over of the charge layer. As a result, the furnace volume becomes even more disproportionate, and from this viewpoint an unjustifiably high energy consumption is required to maintain the indicated melt temperature in it. This is provided by combined plasma-fuel heating of the furnace in which the above burner-plasmatrons are additionally equipped with units for delivery and combustion of a liquid furnace fuel, and the specific energy consumption, without regard for afterburning of the waste gases, is 1.5 kW/kg in electric energy and approximately the same in fuel [16, 17].

In this connection, we may show that the version of separate combustion of wastes in the incinerator at 800–850°C followed by vitrification of the ash residue in a small-volume melting crucible at 1500–1600°C is more energy-saving. In the practice of investigations and experimental developments in this field, both these versions occur [18, 19]; however by virtue of limited use the problem of their comparative energy-economic analysis is far from receiving proper development. In the present context, the problem consists in complex evaluation of the energy consumption by the shaft incinerator and the melting crucible in both versions regardless of the methods of their heating, since here there are particular versions of both plasma and induction heating of the crucible, including their combination [20]. Without resorting to a detailed analysis of all initial transformations and energy losses of each version, we construct a solution by reductio ad absurdum, i.e., on the basis of a general analytical evaluation of the final consumption of heat that is required and is determined directly by the technological body itself and the temperature regime of processing. We employ a traditional balance procedure of heat calculations that is quite reliable for such evaluation, according to which the versions under consideration can be characterized by the following volumetric thermal stress of similar incinerators and furnaces.

Q_{V1} = 0.4–0.5 MW/m^3 pertains to previously known shaft-bed furnaces with low-grade and wood fuel [21] as an analog of combustion of similar wastes at a temperature up to 900°C;

$Q_{V2} \geq 1.5$ MW/m^3 pertains to present-day plasma and shaft blast furnaces [22] as an analog of waste vitrification at a temperature of 1500–1600°C or more.

With reference to [18, 19], where the ratio of the added glass-forming mixture to the ash residue of wastes is determined in a proportion of no more than 1:1, and also with account for approximately a double technological time allowance for holding, degassing, and homogenization of the melt of the glass mass itself the volume of the melting crucible as compared to the furnace-bath of the shaft incinerator can be characterized roughly as follows:

$$\frac{\overline{V}_{\text{cr}}}{\overline{V}_{\text{fur}}} = \frac{V_{\text{ash}} + V_{\text{mix}}}{V_{\text{w}}} \frac{\tau_{\text{g.m}}}{\tau_{\text{w}}} \approx 0.1 , \tag{8}$$

where $V_{\text{w,ash,mix}}$ are the volumes of charging of the wastes, their ash residue, and the added glass-forming mixture, respectively, $V_{\text{fur,cr}}$ are the geometric volumes of the furnace of the shaft incinerator and the individual melting crucible, and $\tau_{\text{w,g.m}}$ are the rate of charging of the wastes and discharging-pouring of the glass mass.

All other things being equal, by definition we can express the energy consumption of the considered versions in terms of the volumetric thermal stresses of the furnace and of the crucible:

$$Q_1 = Q_{V1}\overline{V}_{\text{fur}} + Q_{V2}\overline{V}_{\text{cr}} , \tag{9}$$

$$Q_2 = Q_{V2}\overline{V}_{\text{fur}} \tag{10}$$

and on the basis of the above factors and relation (8) obtain the following comparative estimate for them:

$$\frac{Q_2}{Q_1} = \frac{\dfrac{Q_{V2}}{Q_{V1}}}{1 + \dfrac{Q_{V2}}{Q_{V1}}\dfrac{\overline{V}_{\text{cr}}}{\overline{V}_{\text{fur}}}} \geq 2\,, \tag{11}$$

where $Q_{1,2}$ are the required consumption of heat in the case of separate and combined vitrification of wastes, respectively.

Plasma Blast and Instrinsic Heat Release of the Incinerator. Plasma blast and incinerator heating by electric-arc plasmatrons are characterized by significant heat losses due to air cooling of the current source-rectifiers and water cooling of the plasmatrons themselves, whose intrinsic thermal efficiency does not exceed 75%. In this connection it is expedient to determine and show the conditions when in processing and combustion of rather "dry" solid-organic wastes with a humidity of up to 30% the necessity for such blast naturally disappears. In this case, it is sufficient for the indicated volumetric thermal stress of the incinerator’s furnace to be provided by the intrinsic heat release of such wastes and wood sawdust, the specific heat of combustion of which as a fuel is approximately the same here:

$$Q_{V1}\overline{V}_1 = Q_{\text{w,fil.m}}\,, \tag{12}$$

$$Q_{\text{f}} = (G_{\text{w}} + G_{\text{fil.m}})\, Q^{\text{pr}}_{\text{low(w,fil.m)}}\, \alpha\,, \tag{12$'$}$$

$$Q^{\text{pr}}_{\text{low(w)}} \approx Q^{\text{pr}}_{\text{low(fil.m)}} = Q^{\text{pr}}_{\text{low(w,fil.m)}}\,. \tag{12$''$}$$

If in the general case the structural matching of the square flow cross section of the shaft with the most compact cubic arrangement of the furnace of the shaft incinerator is analytically determined as

$$\overline{V}_{\text{fur}} = S^{1.5}\,, \tag{13}$$

and the specific charge of the filtering material in the shaft cross section and its ratio with charged wastes t are characterized in general form according to [7]:

$$\frac{G_{\text{fil.m}}}{S} = g_{\text{fil.m}}\,, \quad \frac{G_{\text{fil.m}}}{G_{\text{w}}} = m = f(\vartheta, w, \alpha)\,,$$

then condition (12) is fulfilled with the following calculated restriction on the flow cross section of the shaft, above which the furnace volume exceeds the capabilities of the intrinsic heat release of the wastes and the sawdust in this version:

$$S = \left[\frac{g_{\text{fil.m}}\left(1 + \dfrac{1}{m}\right) Q^{\text{pr}}_{\text{low(w,fil.m)}}\, \alpha}{Q_{V1}}\right]^2. \tag{14}$$

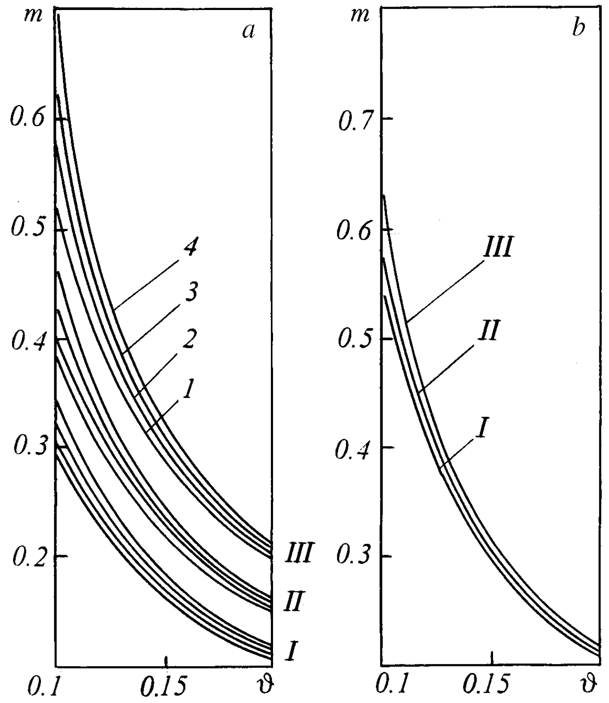

Fig. 3. Calculated dependence of the sawdust-to-wastes charging ratio m on the filtration rate of the waste gases ϑ [7]: a) combustion of solid-organic wastes of different humidity [1) 30%; 2) 40; 3) 50; 4) 50]; b) evaporation of liquid noncombustible wastes with different coefficients of air deficiency [I) $\alpha = 0.3$; II) 0.4; III) 0.5]. m, kg/kg; ϑ, m/sec.

For practical evaluation and implementation of this possibility Fig. 3a provides calculated plots $m = f(\vartheta, w, \alpha)$ obtained for this kind of wastes earlier in [7] provided that the specific intensity of charging of wood sawdust in the shaft cross section is characterized as $g_{\mathrm{fil.m}} = 60\text{–}80$ kg/(m^2·h), while the optimum filtration rate of gases in the shaft is, as indicated above, $\vartheta = 0.1\text{–}0.2$ m/sec. Since the combustion properties of various wastes are very unstable, it is reasonable to implement the possibility of such natural heating of the incinerator and maintain it due to increased charging of wood sawdust with the ratio $m = 0.5\text{–}0.7$ kg/kg, within whose limits the filtration regime of gases is preserved in the indicated rate range. Under these conditions for this kind and humidity of radioactive wastes (textile, woodpulp and paper, wood, and other materials: $Q^{\mathrm{pr}}_{\mathrm{low(w)}} = 1000\text{–}1500$ kJ/kg) the flow cross section of the shaft must be restricted according to (14) to approximately $S = 0.5\text{–}0.7$ m^2, thus supplementing the definition of this parameter and of the capacity of the incinerator itself according to [7], where they have been related only based on the filtration conditions of the waste gases.

The possibility of eliminating the plasma blast is also preserved in processing or in the presence of "heavier" combustible components and admixtures in the indicated wastes, for instance, in the form of solid saturated hydrocarbons and plastics of the PVC type, bituminous resins, etc., which are pyrolyzed much worse than sawdust and therefore require a higher ratio of charging of the sawdust within the limits $m = 3\text{–}4$ kg/kg, for which the content of such wastes in the total processed mass decreases [7] to 15–20%. Under these conditions, it is appropriate to mix them with the other solid-organic wastes so that the ratio between the sawdust and the waste mixture does not go beyond the calculated filtration conditions (see Fig. 3a). In the present case, the specific heat of combustion of such a mixture in (14) is determined as their mass-mean value

$$Q^{\mathrm{pr}}_{\mathrm{low(w,fil.m)}} = Q^{\mathrm{pr}}_{\mathrm{low(w)}} \frac{1}{1+m} Q^{\mathrm{pr}}_{\mathrm{low(fil.m)}} \frac{m}{1+m}\,, \tag{15}$$

$$Q^{\mathrm{pr}}_{\mathrm{low(w)}} = \Sigma\ Q^{\mathrm{pr}}_{\mathrm{low}i} C_i\,, \tag{15$'$}$$

where $Q^{\mathrm{pr}}_{\mathrm{low}i}$ and C_i are, respectively, the specific heat of combustion and the mass content of the indicated components in the mixture of wastes.

In processing of "moist" and biological wastes with a humidity of up to 50–60%, when their combustion properties abruptly decrease and the furnace cannot be heated only by the heat of combustion of the "dry" filtering material of sawdust, use is made of the plasma blast of the incinerator, as indicated above. Neglecting the intrinsic heat of combustion of such wastes and determining the thermal power of the plasma blast by (1)–(3), we use the following equation and the components of the volumetric thermal stress of the furnace:

$$Q_{V1}\overline{V}_1 = Q_{\mathrm{fil.m}} + Q_{\mathrm{pl}} - Q_{\mathrm{ev,s.st}}\,, \tag{16}$$

$$Q_{\mathrm{fil.m}} = G_{\mathrm{fil.m}} Q^{\mathrm{pr}}_{\mathrm{low(fil.m)}}\, \alpha\,, \tag{16$'$}$$

$$Q_{\mathrm{pl}} = \psi_{\mathrm{pl}}\,(G_{\mathrm{w}} + G_{\mathrm{fil.m}})\, v_{0\mathrm{(w,fil.m)}}\, \rho_0 \alpha\, \overline{c}_p t_{\mathrm{pl}}\,, \tag{16$''$}$$

$$Q_{\mathrm{ev,s.st}} = G_{\mathrm{w}} w\,(r + i''_{\mathrm{s.st}})\,, \tag{16$'''$}$$

where $Q_{\mathrm{ev,s.st}}$ is the consumption of heat by evaporation of the indicated excess moisture of wastes and by superheating of the formed steam to the furnace temperature, from which on the basis of the geometric characteristic of the furnace and the incinerator shaft and using expressions (13) and (14) we obtain the following calculated expression:

$$\overline{\psi}_{\mathrm{pl}} = \frac{V_{0\mathrm{(pl)}}}{V_{0\mathrm{(w.fil.m)}}} = \frac{\dfrac{Q^{\mathrm{pr}}_{\mathrm{low(fil.m)}}\,\alpha}{m} + w\,(r + i''_{\mathrm{s.st}})}{\left(1 + \dfrac{1}{m}\right) v_{0\mathrm{(w.fil.m)}}\, \rho_0 \overline{c}_p t_{\mathrm{pl}}}\,, \tag{17}$$

according to which the relative volume of the plasma blast in processing of wastes with this moisture content, as indicated above, can be evaluated as approximately ψ_{pl} = 10–20%.

A maximim volume of the plasma blast is needed in evaporation of noncombustible aqueous solutions and suspensions of radioactive wastes with a humidity of 100% when the volume of air supply to the furnace is dictated by the needs of pyrolysis and combustion only of the filtering material, while the volume and the heat content of the plasma blast of this air according to (1)–(3) are corrected in the form

$$V_{0\mathrm{(fil.m)}} = G_{\mathrm{fil.m}} v_{0\mathrm{(fil.m)}}\, \alpha\,, \tag{18}$$

$$Q_{\mathrm{pl}} = \psi_{\mathrm{pl}} G_{\mathrm{fil.m}} v_{0\mathrm{(fil.m)}}\, \rho_0 \alpha\, \overline{c}_p\, t_{\mathrm{pl}}\,. \tag{19}$$

Using the same geometric characteristics of the furnace and the shaft from (13) and (14), we obtain from (16)–(19) the following index of the relative volume of the plasma blast under evaporation conditions:

$$\psi_{\mathrm{pl}} = \frac{V_{0(\mathrm{pl})}}{V_{0(\mathrm{fil.m})}} = \frac{\dfrac{Q^{\mathrm{pr}}_{\mathrm{low(fil.m)}}\,\alpha}{m} + r + i''_{\mathrm{s.st}}}{v_{0(\mathrm{fil.m})}\,\rho_0 \alpha\,\bar{c}_p t_{\mathrm{s.st}}}\,, \tag{20}$$

the most economical and efficient implementation of which in this regime is achieved, according to [7], with the charging of the filtering material of sawdust being within the limits m = 0.5–0.7 kg/liter and with the maximum possible air supply $\alpha = 0.5$ (see Fig. 3b). In this case, the intrinsic heat release of the sawdust is also at its maximum, the mode of filtration of the waste gases corresponds to their optimum velocity, approximately, $\vartheta = 0.1$ m/sec, and the relative volume of the plasma blast of air in accordance with (21) is, as has been indicated above, ψ_{pl} = 50–70%. Here, possible versions of the coefficient of air deficiency in the furnace, as is seen in Fig. 3b, have practically no effect on the regime of filtration of the waste gases, since their volume under evaporation conditions is determined mainly by the volume of the evaporated moisture.

Conclusions. The results of this analysis make it possible to substantiate a priori the volumes and energy consumption of plasma blast in different regimes and versions of thermal processing of wastes by this method and also to evaluate the main technical characteristics and the overall dimensions of a shaft-filtration incinerator for its implementation, which are given in Table 1. As a note to the table we would like to add that for nontoxic "dry" radioactive wastes the temperature of afterburning of the waste gases decreases from 2000 to 1000°C in version 1, as a result of which, all other things being equal, the specific energy consumption in processing also undergoes an almost twofold decrease to 1 kW·h/kg. The results obtained allow us to draw the following conclusions, which have become the basis of a project, implemented by the ASC HMTI, on processing of a wide range of toxic industrial wastes by the suggested method:

1. The known filtration properties of wood sawdust and their use in thermal processing of wastes by the suggested method allow up to a 1–2% decrease in the aerosol removal of the waste gases. In this case, plasma blast of the process by air burner-plasmatrons reduces the volume of the waste gases by a factor of no less than 3–4, thus implementing the most efficient conditions for their filtration in the proper layer of charging of wastes and sawdust. Moreover, the indicated burner-plasmatrons provide evaporation of liquid and noncombustible wastes and also high-temperature plasma afterburning of the waste gases in processing of halogen-containing and a number of other toxic wastes.

2. All other things being equal, separate combustion of radioactive wastes in a shaft-filtration incinerator followed by vitrification of their ash residue in a low-volume melting crucible is twice as energy-saving as the version of their combined implementation in a common melting furnace of similar type, which makes it possible to consider this separate processing to be the most appropriate one.

3. The possibility of eliminating the plasma blast of the incinerator in combustion of rather "dry" and combustible wastes with a humidity of up to 30% lies in a certain calculated restriction of the shaft cross section and the furnace volume of the incinerator, at which the input and the heat release of wastes with a filtering material of sawdust meet the conditions of volume heating of the furnace up to the temperature of combustion by the suggested method.

4. In processing of "moist" wastes with a higher moisture content, the plasma blast of the incinerator amounts to 10–20% of the total air supply and, under the condition of high-temperature plasma afterburning of toxic gases, is characterized by a total consumption of 2–3 kW·h of electric energy per kg of wastes. In the version of combustion of "dry" and nontoxic wastes the consumption of electric energy is determined only by the plasma afterburning of the waste gases and decreases to approximately 1 kW·h/kg. In evaporation of aqueous solutions and suspensions of radioactive wastes these characteristics increase up to 50–70% and 4–5 kW·h/kg, respectively; the energy consumption of the plasma blast in the furnace is 30–50% made up due to the intrinsic heat release of the filtering material.

TABLE 1. Parameters and Energy Consumption of Thermal Processing of Wastes in a Shaft Incinerator with Plasma Blast and a Combustible Filtering Material (wood sawdust)

Stages, parameters, and energy consumption of processing (sawdust humidity is 30%)	Kinds and versions of processing of wastes		
	"dry" and halogen-containing radioactive wastes (humidity 30%)	"moist" and biological wastes (humidity 60%)	evaporation of acqueous solutions and suspensions of radioactive wastes
	1	2	3
Charging of wastes and sawdust (liquid wastes are sprayed in the furnace)			
Charging of solid wastes, kg/h	85	70	–
Filling of wood sawdust, kg/h	25	35	35
Feed of liquid wastes, liter/h	–	–	50
Charging ratio, kg/kg	0.3	0.5	0.7
Combustion and evaporation of wastes in the furnace (the working volume of the furnace is 0.3 m^3)			
Excess-air coefficient	0.3	0.4	0.5
Total air supply, nm^3/h	100	120	40
Volume of plasma blast, nm^3/h	–	12	24
Thermal power of blast, kW	–	60	120
Heat release of wastes/sawdust, kW	120	60	60
Heat consumption by evaporation, kW	–	–	60
Total heat release in the furnace, kW	120	120	120
Volumetric thermal stress of the furnace, MW/m^3	0.4	0.4	0.4
Afterburning of gases in the cyclone chamber (the chamber volume is 0.06 m^3)			
Temperature in the afterburning chamber, $^{\circ}$C	2000	1500	1000
Total air supply, nm^3/h	240	180	50
Volume of plasma blast, nm^3/h	24	18	10
Thermal power of blast, kW	120	90	60
Volumetric thermal stress of the chamber, MW/m^3	2.0	1.5	1.0
Energy consumption of processing (the thermal efficiency of the plasmatrons is 75%)			
Total energy consumption of the plasmatrons, kW	180	200	240
Specific consumption per kg of wastes, kW·h/kg, including:	2.1	2.7	4.8
by furnace heating, kW·h/kg	–	1.1	3.2
by the filtering material, %	100	50	33

NOTATION

$G_{\text{w,fil.m,f,pl}}$, mass flow rate of the wastes, the filtering material, the fuel, and the plasma blast of air, respectively; Q_{pl}, t_{pl}, and c_p, thermal power of the blast, mass-mean temperature, and equilibrium heat capacity of the plasma air at the given temperature, respectively; $Q_{\text{w,fil.m,f}}$, heat release of the combustible wastes, the filtering material, and the fuel; $Q^{\text{pr}}_{\text{low(w,fil.m,f)}}$, their specific heat of combustion; ρ_0, V_0, and v_0, density and total and specific consumption of air in combustion of 1 kg of the components indicated above, respectively; α, pyrolytic coefficient of air deficiency in the incinerator furnace; w, relative humidity of the wastes; r, specific heat of moisture evaporation (vaporization); $i''_{\text{s.st}}$, enthalpy of the superheated steam (at the furnace temperature); ϑ, filtration rate of gases in the shaft; S, area of the flow cross section of the shaft. Superscripts and subscripts: w, wastes; fil.m, filtering material; f, fuel; pl, plasma; ash, ash and ash residue; mix, mixture for ash vitrification; g.m, glass mass; out, outgoing gases; s.st, superheated steam; ev, evaporation; com, combustion; pyr, pyrolysis; fur, furnace; cr, crucible; 0, at a temperature of 20^{o}C; pr, process; low, low (heats of fuel combustion).

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