Journal of Engineering Physics and Thermophysics, Vol. 79, No. 4, 2006

ANALYSIS AND SIMULATION OF THE PROCESS OF MEDICOBIOLOGICAL WASTE TREATMENT IN A PLASMA CHAMBER INCINERATOR

A. L. Mossé and V. V. Savchin

UDC 261.039.7:533

Analysis of the composition and the degree of toxicity of medicobiological wastes has been performed with the use of the results of investigations made in different countries. It has been shown that such wastes are highly hazardous to ecology and a universal technology of their management is needed. We have developed and tested a plasma chamber incinerator for plasmothermal treatment of medicobiological waste. To optimize the operating conditions of the facility and prevent chemical and thermal pollution of the environment, we have constructed a model of thermal calculation of the plasma chamber incinerator.

Formulation of the Problem . The problem of disinfection and treatment of medicobiological wastes is the focus of many countries in the world. This is due to the rapid increase in the amount of high-toxicity and infected waste of medical institutions and medicobiological industries [1, 2] that contain viruses, microbes, strains, and therapeutic medicines containing radionuclides and new biological forms — priones which are the most resistant to high temperatures. Therefore, treatment of this kind of waste calls for the most effective and universal technology. The main conventional methods of treatment of medicobiological waste are thermal methods, of which the plasmothermal one is the most universal and reliable. To realize this method and obtain plasma temperatures, electric-arc generators of thermal plasma — plasmatrons — are used.

Analysis of the Composition of Waste. It is known [2, 3] that production of medicines yields not only the required products and substances, but also various wastes: toxic mother solutions, vat residues, filter cloth, activated carbon, etc. A large quantity of such products is also formed in hospitals upon giving medical aid to patients and as a result of treatment of medical devices and equipment. Thus, medicobiological waste include food refuse, paper, wood, textile, leather, rubber, various kinds of plastics, glass, metal, ceramics, and many other tings. Various medical and chemical preparations can also enter into their composition. The above kinds of wastes consist of 50–60 vol.% of fluids, 20–40% of solids, and 10–20% of gases. In most cases, they are not sorted and, as a rule, and have a highly complex composition that is not amenable to exact identification. At the same time, the waste treatment standards adopted in, e.g., Japan, Italy, and in Taiwan [4] require their presorting by composition. Therefore, in [5] their average elemental composition is often given (Table 1). The content of inorganic matter in the composition of medicobiological waste can reach about 50%, and their calorific value is 4012 kcal/kg.

Sanitary-hygienic analyses of solid medicobiological wastes performed both in the Republic of Belarus and abroad [1] show that they are a more serious hazard to the environment than the majority of secondary chemical products.

Technology of Medicobiological Waste Treatment. For thermal treatment of medicobiological waste, fuel or plasma furnaces, where waste is incinerated in an oxygen-containing medium or pyrolyzed in a reducing atmosphere, are used. The most promising variant of this technology that has been actively developed in recent years is the use of electric-arc plasma incinerators.

The experimental results accumulated at the department of plasma physics and chemistry of the A. V. Luikov Heat and Mass Transfer Institute (HMTI of the NAS of Belarus) [3], as well as the data obtained in other organizations show that the plasma method is the most reliable and ecologically clean method for treating medicobiological waste and liquid secondary products formed in the production of synthetic medicines (e.g., such as vat residues of the

---

A. V. Luikov Heat and Mass Transfer Institute, National Academy of Sciences of Belarus, 15 P. Brovka Str., Minsk, 220072, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 79, No. 4, pp. 12–16, July–August, 2006. Original article submitted March 28, 2005.

TABLE 1. Elemental Composition of Medicobiological Waste

Substance	Mass fraction of component, %	Substance	Mass fraction of component, %
Water	32.31	Oxygen	6.29
Ash	7.00	Nitrogen	8.16
Carbon	34.15	Sulfur	0.94
Hydrogen	5.85	Chlorine	5.30

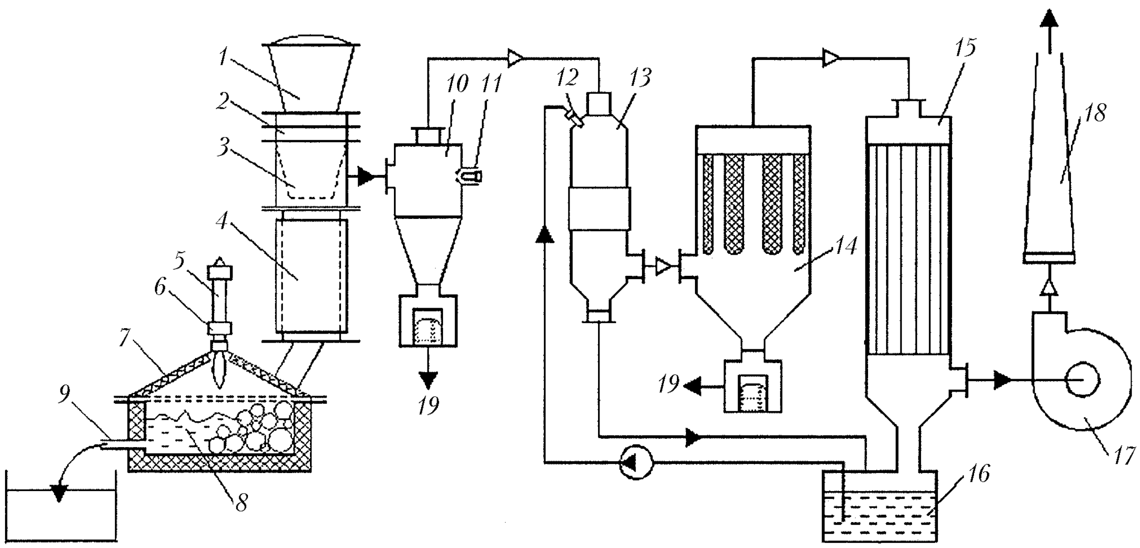

Fig. 1. Diagram of the facility for treatment of medicobiological waste: 1) loading bin; 2) loading gate; 3) sluice chamber; 4) loading shaft; 5) PDS-3 plasmatron; 6) device for conveying additional gas; 7) incineration chamber; 8) waste material; 9) system of removing melt slugs; 10) secondary incinerator; 11) plasmatron (burner) of the secondary incinerator; 12) input of coolant into the heat-exchanger; 13) heat-exchanger; 14) screen filter; 15) condenser; 16) collector of condensed liquid; 17) fan; 18) pipes; 19) exit (to repeated treatment).

technology of producing aminoketone chlorohydrate, amidopyrine, acetoacetic acid, phthivaside, paranitroacetophenone, hydrochloride metacycline, levomycetin, etc. [3].

In the cases where volumes of medicobiological waste to be treated are not large, e.g., in individual hospitals, the use of plasma camera batch incinerators is justified. In this case, the transportation operation is absent, which, in the opinion of specialists, lowers the risk of terrorist actions. To this end, a facility for thermal treatment (destruction) of lump or bagged organic and inorganic waste of different origin has been developed and tested. The main condition of its operation is the possibility of heating lump or bagged waste by a high-temperature gas flow to the temperature of complete incineration of the organic part and melting of the inorganic part (ash) with the aim of obtaining a homogeneous melt and its subsequent removal. The facility is schematically represented in Fig. 1. It incorporates an electric-arc plasmatron, a plasma incineration chamber, energy-, gas-, and water-supply systems (for plasmatron operation and incinerator cooling), a waste charging device, a secondary incinerator, a gas purifying unit, as well as a device for removing ash. Heating of the chamber and treatment of waste in it are carried out directly under the action of a plasma jet with the initial mass-average temperature of 4500–5000 K.

The facility uses a rod electric-discharge plasmatron of the type of PDS-3 with air stabilization of an arc with a power of 50 kW and a fairly long service life widely used for realizing various technological processes.

The incineration chamber made of stainless steel and lined with a special refractory material (its melting temperature is above 1200^{o}C) is hermetically closed with a lid. The chamber case is equipped with side cooled panels. On one of its walls there is a side hole and a device for discharging ash melt into containers is mounted. The lid of the incineration chamber is a flange cooled by running water on which an electric-arc plasmatron is installed.

One-time loading of bagged waste into the chamber of power 50 kW about 6–10 kg, the treatment time of such a bag is about 7–10 min depending on the waste composition. Then the plasmatron is switched off, the melt of the inorganic part of the waste is discharged into a special container, and the chamber cools done for 10–15 min. At this point the single operating cycle of the chamber is finished, and its total time with allowance for cooling is ~30 min. After this the incinerator is ready for a new loading and switching on of operation.

The proposed incinerator is a fairly universal device, since waste of any type (organic waste with toxic impurities, halogen-organic, medicobiological, etc.) can be bagged simultaneously and be destroyed directly at the site of its gathering, excluding the stage of transportation.

Model of Thermal calculation of the Plasma Chamber Incinerator. Treatment of medicobiological waste may lead to both environment pollution with various toxic substances and thermal pollution depending on the operating conditions of the incinerator. We propose a model of thermal calculation of the chamber incinerator for choosing optimal operating conditions of the facility.

Consider the thermal balance of the incineration chamber in one operating cycle. The energy input by the plasmatron is

$$Q_{\mathrm{pl}} = \eta N t = \eta I U t \,.$$

The specific heat of waste incineration is defined by the formula

$$q = h_{\mathrm{C}}\,[\mathrm{C}] + h_{\mathrm{H}}\,[\mathrm{H}] - h_{\mathrm{H_2O}}\,(9\,[\mathrm{H}] - [\mathrm{H_2O}]) - h_{\mathrm{O-S}}\,([\mathrm{O}] - [\mathrm{S}]) \,.$$

The thermal effect of reactions is calculated proceeding from the stoichiometric equations of reactions in the incinerator chamber. On the inside, the incinerator chamber is lined with an Al_2O_3-based material, and the layer thickness is 5 cm. The heat loss through the lining is calculated as

$$Q_{\mathrm{h.s}} = 2\pi L K \frac{T_{\mathrm{s,h}} - T_{\mathrm{s,c}}}{\ln \dfrac{d_{\mathrm{s,c}}}{d_{\mathrm{s,h}}}} \,.$$

This energy is carried off with the cooling water, whose flow rate is defined as

$$D_{\mathrm{w}} = \frac{Q_{\mathrm{h.s}}}{c_{\mathrm{w}}\,(T_{\mathrm{w2}} - T_{\mathrm{w1}})} \,.$$

The heat loss due to radiative and convective transfer into the environment is

$$Q_{\mathrm{h.a}} = Q_{\mathrm{h.r}} + Q_{\mathrm{h.c}} \,.$$

The heat emitted into the environment from 1 m^2 of the incinerator surface is

$$Q_{\mathrm{h.r}} = C_0 E \left[\left(\frac{T_{\mathrm{wall.c}}}{100} \right)^4 - \left(\frac{T_{\mathrm{a}}}{100} \right)^4 \right] .$$

The heat lost due to air convection from 1 m^2 of the incinerator surface is

$$Q_{\mathrm{h.c}} = C\,(T_{\mathrm{wall.c}} - T_{\mathrm{a}}) \,.$$

Results of Calculation of the Process of Incineration of Waste in the Plasma Chamber Incinerator. We have made calculations of the process of incineration of medicobiological waste in the plasma chamber incinerator on the basis of the proposed model. In this technology of treating medicobiological waste, a PDS-3-type plasmatron (power of 50 kW) is used as a burner, and the plasma-forming gas is atmospheric air, whose pressure at the inlet to the plasmatron is 5 atm. The air flow rate in the plasmatron is 3 g/sec.

TABLE 2. Approximate Composition of Gas Entering the Secondary Incinerator

Substance	Mass fraction of component, %	Substance	Mass fraction of component, %
Monoxide	61.8	Carbon	1.6
		Hydrogen	6.2
Nitrogen and other gases of carbon	29.6	Sulfur	0.8

TABLE 3. Approximate Composition of Gas at the Exit from the Secondary Incinerator

Substance	Mass fraction of component, %	Substance	Mass fraction of component, %
Carbon dioxide	18.3	Chlorine	0.76
Water	12.2	Nitrogen	68
Sulfur dioxide	0.27	Other gases	0.47

In the general case, in the incinerator chamber the process of pyrolysis of the organic mass of waste proceeds, leading to the formation of gaseous, liquid, resinous, and solid components, having a high calorific value, and melting of the inorganic part of waste occurs. The relative content of partial components of the process depends on the content of water and the temperature of pyrolysis. The pyrolysis temperature, however, is so high that volatile, liquid organic, and resinous substances and cellulose under its action breakdown into simpler elements, which in turn, following the laws of chemical kinetics, form simple chemical compounds at this temperature. In so doing, the basic equations of chemical reactions are [5]:

$$2C + O_2 = 2CO + 58.86 \text{ kcal/mole} ,$$

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

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

Because of its small fraction, sulfur makes an insignificant contribution to the heat balance and is excluded from consideration. It is assumed that nitrogen from the waste material transforms to molecular nitrogen and does not influence the process energy. However, because of the deficiency of oxygen contained in the air that is used to obtain low-molecular plasma, only partial combustion of organic matter in the incinerator chamber occurs, since complete combustion of 1 kg of medicobiological waste requires 5.7 kg of air. Thus, only the first and the second reactions take place. Under the given operating conditions the process of pyrolysis proceeds with absorption of energy of 5.9 MJ. The average temperature of gases in the incineration chamber is 1500^{o}C. The mass of pyrolysis and oxidation products discharged in one working cycle (10 min) is 7.4 kg. The gas from the incinerator chamber is conveyed into a special secondary incinerator. The gas composition is given in Table 2. In one technological cycle, 4.7 MJ of energy are abstracted from the incineration chamber with cooling water (heating of the cooling water by 30^{o} at a consumption of 62 g/sec). The energy losses due to the radiation and convective transfer into the environment are not large — only 219 kJ per cycle. For heating and melting of slag 630 kJ are required. Upon completion of treatment of the waste the ash melt is drawn off into ceramic containers.

Air with a flow rate of 54 g/sec is additionally conveyed into the secondary incinerator to maintain the reactions of oxidation of carbon and carbon monoxide to carbon dioxide, of hydrogen — to water, and of sulfur — to sulfur dioxide. In so doing, 106 MJ of energy is released. In one working cycle (10 min) 41.7 kg of gases with a temperature of 2500^{o}C are drawn off from the secondary incinerator. The composition of the gaseous mixture is given in Table 3. Then in the heat-exchanger the gaseous mixture is cooled (the cooling water is heated by 30^{o}C at a flow rate of 1.4 kg/sec). The gaseous mixture passes through the purification system and is released into the atmosphere.

Thus, the investigations have revealed that medicobiological wastes represent a mixture of various substances, including highly toxic and radioactive ones. Determination of the composition of wastes and their preliminary separation present difficulties. In the present paper, one variant of destruction of waste in a plasma chamber batch incinerator is proposed. To prevent chemical and thermal pollution of the environment and choose the optimal operating conditions of the facility, a model of the calculation of the distribution of thermal flows in the system is proposed. The chemical composition of elements contained in medicobiological waste and the compositions of the gaseous mixture at the exit from the plasma incineration chamber and the secondary incinerator have been calculated with regard for the thermal flows formed in the plasma incinerator.

NOTATION

C_0 = 5.67 W/(m^2·K^4), Stefan–Boltzmann constant; C = 16.5 W/(m^2·C), coefficient of heat transfer from the incinerator walls due to air convection; c_w, specific density of water, J/(kg·K); D_w, water discharge, kg/sec; $d_{s.h}$ and $d_{s.c}$, inner and outer diameters of lining, m; E = 0.95 J, emissivity into the environment for incinerator walls, J; h_C = 81 kcal/kg, empirical value of carbon formation heat; h_H = 300 kcal/kg, empirical value of hydrogen formation heat; h_{H_2O} = 6 kcal/kg, empirical value of steam generation heat; $h_{O–S}$ = 26 kcal/kg, empirical value of sulfur oxide formation heat; I, current intensity fed to the plasmatron, A; K = 1.7 W/(m·^{o}C), heat conductivity coefficient of the lining material; L, height of the incinerator chamber, m; N, power fed to the plasmatron, W; q, specific combustion heat of the waste material, J/kg; Q, energy (heat), J; t, working cycle time of the facility, sec; T, temperature, K; U, voltage applied to the plasmatron, V; η, plasmatron efficiency. Subscripts: a, atmospheric air (environment); c, cold; h, hot; h.a, heat loss into the environment; h.c, heat loss due to convective transfer of surrounding air; h.r, heat loss due to emission into the environment; h.s, heat loss through the lining; pl, plasmatron; s, lining surface; w, water; w1 and w2, water in the cooling system at the entrance and exit, respectively; wall.c, outer cold surface of the incinerator.

REFERENCES

1. Y. Penishkevych, N. Zhyltsova, S. Pasechny, I. Maksyuta, and Y. Gomza, Improvement of Medical Wastes Management in Ukraine, Kyiv (2001).
2. Y. A. Moten, Guides to Pollution Prevention of Selected Hospital Waste Streams, Nat. Univ.of Sci. and Technol., Rawalpindi (1989).
3. A. L. Mossé, A. V. Gorbunov, and E. M. Ermolaeva, *Plasma Processing of Toxic Organic and Halogen-Containing Waste. Problems and Possibilites of Contamination* [in Russian], Preprint No. 2 of the A. V. Luikov Heat and Mass Transfer Institute, National Academy of Sciences of Belarus, Minsk (2003).
4. M. Distelmans, Optimal waste pretreatment method for resource recovery, biological processing and thermal recovery. SEGHERbetter technology for solids+air, Willebroek, Belgium (2001).
5. V. S. Cherednichenko, A. M. Kazanov, A. S. An'shakov, et al., *Modern Methods of Treatment of Solid Waste* [in Russian], IT SO RAN, Novosibirsk (1995).