Journal of Engineering Physics and Thermophysics, Vol. 70, No. 4, 1997

CALCULATION OF THE FILTERING PROPERTIES OF A CHARGED BED IN A SHAFT PROCESS OF PLASMOTHERMAL TREATMENT OF RADIOACTIVE WASTE

A. L. Mossé, V. A. Kalitko,
A. Marotta, and E. M. Ermolaeva

UDC 621.039.7:533.9

We consider a stationary problem of the filtration and precipitation of radioactive aerosols in a charged dense bed in a shaft process of plasmothermal treatment of solid lump radioactive waste for immobilization in a melt of a glass-forming charge. We perform a comparative analysis of calculations with known data and characteristics of absorption for fine and coarse filters and assess the filtering properties of the bed for the problem considered. The results of calculation are confirmed by the available experimental data.

Introduction. The removal and burial of a wide range of unsorted solid radioactive waste (RAW) of low and moderate activity that contains different organic admixtures and additions usually involve thermal treatment, which considerably reduces the burial volume [1]. Considering the subsequent conditions and requirements for burial, it is advisable that RAW be thermally treated up to immobilization in a glass-forming melt of a charge. This considerably increases the reliability of burial and reduces the amount of work to be done when such waste is kept in the form of glass blocks with a multiple degree of protection against penetration into the ambient [2]. Along with the well-known two-stage technology of such treatment, when burning and vitrification of the ash residue of RAW are carried out in different furnaces and apparatuses [3], a more effective and economic technical solution consists in a shaft process of thermal treatment, in which, by the well-known analogy with a blast-furnace process, thermolysis, combustion and melting of RAW occur in a single shaft melting furnace together with vitrification of the charge. Then the use of plasma sources of heating in such a process allows one to easily attain the needed melting temperatures and, moreover, to produce a 4–5-fold reduction in the volume of effluent gases compared with conventional heating of a furnace by firing fuel additionally [4]. As a result, the release of radioactive aerosols from such a furnace is also decreased, and this proportionally reduces the load on the system of gas purification and prolongs its life. Moreover, the benefit from the reduction in the extent of gas purification due to plasma heating of the furnace is complemented by that from filtration of exhaust gases in the charged bed of RAW, and thus the escape of radioactivity can be reduced to 1–2%, as shown by the well-known experimental works carried out at the Scientific-Industrial Association "Radon" [5].

Usually, the escape of radioactivity with ash when using conventional methods of burning RAW in furnaces and chamber stokers is determined precisely by the entrainment of aerosols and is characterized by a value on the order of 5–10%, when the remaining 90–95% of the RAW activity is fixed in the ash [1]. A smaller escape in these cases is simply unreal, since it is impossible to attain a smaller entrainment of ash and because of the fact that even at ordinary temperatures of combustion of the order of 850–900°C there is a vapor-gas escape of radioactivity of such low-temperaure nuclides as Y and Cs of 1–2% and above. As the temperature increases, this component of the radioactivity escape increases and may attain 30% at 1100°C [5]. Therefore, a combination of the plasma method of heating with the shaft technology of process implementation at 1400–1500°C and above makes it possible to avoid not only aerosol, but also vapor-gas escape of radioactivity, since the temperature of the exhaust gases decreases to 300–400°C along the height of the shaft and the indicated radionuclides condense.

Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute of the Academy of Sciences of Belarus," Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 70, No. 4, pp. 614-629, July-August, 1997. Original article submitted February 26, 1997.

1062-0125/97/7004-0609$18.00

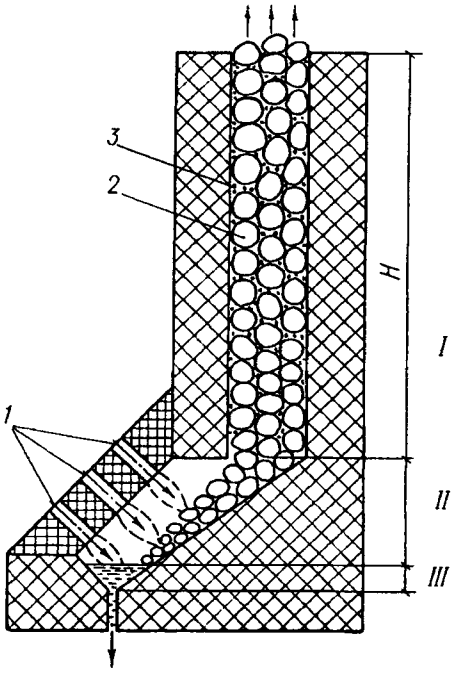

Fig. 1. General arrangement and principle of operation of shaft furnace for plasmothermal treatment of RAW: 1) plasma burners (plasmatrons); 2) lump bed of RAW charge; 3) filtering additions and fillers of the bed (I, zone of filtration; II, zone of thermolysis; III, zone and bath of melting).

Exceptions are the so-called "hot" radioactive particles of submicron level of the order of 0.1 μm, which present a problem and are formed on combustion of RAW at an elevated temperature [5]. Even in the most advanced HEPA and Petryakov filters [6], particles of this size are characterized by the maximum slippage factor, which is known to be due to their position at the boundary relative to the diffusional and inertial-viscous mechanisms of their transfer and precipitation, when none of these is dominant. The imperfection of such filters can be attributed to a very thin filtering layer of only 1–2 mm for both Petryakov's cloth and the sieve structure of HEPA filters. We may expect (and it was proved by the experiments of [5]) that this problem can be partially solved by using a thick filtering bed of the order of 1–2 m, as well as a certain composition of the filtering charge of the bed.

In order to realize these possibilities and advantages, at the Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute of the Academy of Sciences of Belarus" we, together with the Scientific Industrial Association "Rodon," are carrying out investigations and developments for creating such a plasma charge furnace, whose arrangement and principle of operation are presented in Fig. 1. By analogy with the blast-furnace process, RAW is charged from above, while electric-arc plasma burners (plasmatrons) located at the bottom of the furnace produce thermolysis and melt the ash residues of RAW mixed with a glass-forming charge, with the melt being discharged from the drain hole at the bottom. Leaving aside in this case consideration of the specific technology of charging, the system for pouring and containerizing the melt at the bottom of the furnace, just as the system of gas purification at the top, we will point out only the zones of the furnace process from above downward following the charging of waste and defining them in the order in which they are considered in the present work: I is the zone of filtration of stack gases in a shaft in a dense charged bed; II is the zone of the thermolysis of waste on the inclined hearth of the furnace; III is the zone and bath of the melting of waste.

Statement and Solution of the Problem. In the case of regular periodic charging of RAW from above, as shown in Fig. 1, the process of the filtration of gases in the bed along the height of the furnace shaft can be regarded as stationary, in which the concentration of aerosol along the path of stack gases decrease but remains constant in time in each lateral cross-section of the bed. The process considered can be transformed into the flow of aerosol streams along the length (height) of the bed in its curvilinear (twisting) channels, the effective radius of which r_{ef} is determined by the radius (size) of the lumps and granules of the charged bed R in the furnace considered [7]:

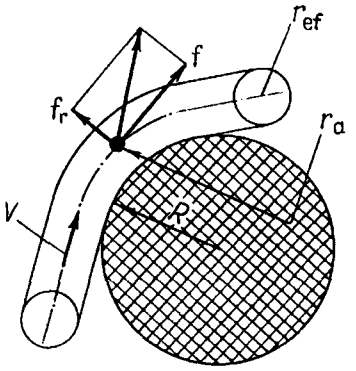

Fig. 2. Computational scheme for the problem of filtration and precipitation of porous particles in a charged bed of waste to be treated.

$$r_{ef} = \frac{4}{3}\frac{\varepsilon}{1-\varepsilon}R, \tag{1}$$

where ε is the bed porosity.

Placing emphasis on the application of such simple filtering additions and fillers in the RAW charge as wood chips or sawdust, whose resinous deposits at 300–400°C lead to the so-called condensation effect and coagulation of solid and liquid aerosols, we assume that the conventional walls of the channels considered completely absorb the particles contacting them. Here, we take into account both standard mechanisms of the transfer and precipitation of particles, namely, diffusional for small particles and inertial-viscous for larger ones. In particular, moving together with the gas flow along the curved path of the channel R (Fig. 2), small particles can approach the wall and contact it only diffusionally. And conversely, under the influence of the inertial force f, the large particles depart from the curvature of the channel and also contact the wall. Thus, in both cases the longitudinal flow of the aerosols is accompanied by radial transfer and absorption of particles near the walls of the channels considered. This is represented in vector form by the following ordinary system of equations of mass transfer and diffusion of particles (molecular-kinetic model):

$$\rho \mathbf{V}\,\nabla C = -\operatorname{div}\mathbf{j}, \tag{2}$$

$$\mathbf{j} = -\rho D\,\nabla C + \rho C\mathbf{U}, \tag{3}$$

$$U \cong V, \tag{4}$$

$$\mathbf{U} = B\,\mathbf{f}, \tag{5}$$

$$B = \frac{D}{kT} = \frac{1}{6\pi\mu r_a} = \frac{D}{kT}. \tag{6}$$

According to the computational scheme in Fig. 2, taking into consideration only the radial, i.e., centrifugal, component of the viscosity force f:

$$f_r = \frac{mU^2}{R}, \tag{7}$$

and neglecting the longitudinal mechanism of the diffusion of particles along the streams considered, with allowance for Eqs. (2)-(7) we have the following initial equation of the process:

$$\rho V \frac{\partial C}{\partial x} - \rho D \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial C}{\partial r} \right) + \rho B \left(f_r \frac{\partial C}{\partial r} + C \frac{\partial f_r}{\partial r} \right) = 0 , \tag{8}$$

For its analytical solution we avail ourselves of the assumption of additivity in the action of each of the two indicated mechanisms of transfer. In this case the diffusional term of Eq. (8)

$$\rho V \frac{\partial C}{\partial x} - \rho D \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial C}{\partial r} \right) = 0 \tag{9}$$

has a known solution in the form of the sum of an infinite series of separate solutions with the partial coefficients A_i and a_i for the channel cross-section mean concentration of particles $\overline{C}$:

$$\overline{C}(x) = C_0 \sum_{i=1}^{\infty} A_i \exp \left(- a_i^2 \frac{D}{V r_{ef}} \frac{x}{r_{ef}} \right) , \tag{10}$$

where C_0 is the initial concentration of particles; A_i are the coefficients of the converging series, for which $\sum_{i=1}^{\infty} A_i = 1$ and $A_1 = 0.715$, $A_2 = 0.164$, ...; a_i are the coefficients of the series $a_1 = 1.35$, $a_2 = 3.34$, ...; for engineering-physical calculations and estimations it is possible to restrict ourselves to only the first terms of series (10) with the coefficients A_1 and a_1.

For the second, inertial-viscous mechanism of the transfer of particles to the wall under the action of only the radial component of the force (7), we obtain a simple equation ($\partial C / \partial r = 0$)

$$\rho V \frac{\partial C}{\partial x} + \rho C B \frac{\partial f_r}{\partial r} = 0 , \tag{11}$$

whose solution, by analogy with Eq. (10) and allowance for Eqs. (5)-(6), takes the form

$$\overline{C}(x) = C_0 \exp \left(- \frac{mVD}{kTR} \frac{x}{R} \right) . \tag{12}$$

Using Eq. (1) to determine the relationship between r_{ef} and R, we admit a general solution of (8) in the form of an exponential sum of solutions (10) and (12), of which solution (10) is limited to the first terms of the series A_1 and a_1:

$$\overline{C}(x) \cong C_0 A_1 \exp \left[- \left(\frac{9}{16} a_1^2 \frac{D}{VR} \left(\frac{1 - \varepsilon}{\varepsilon} \right)^2 + \frac{mVD}{kTR} \right) \frac{x}{R} \right] , \tag{13}$$

$$A_1 = 0.715 , \quad a_1 = 1.35 ;$$

$$\overline{C}(x) \cong 0.715 C_0 \exp \left[- \left(\frac{D}{VR} \left(\frac{1 - \varepsilon}{\varepsilon} \right)^2 + \frac{mVD}{kTR} \right) \frac{x}{R} \right] . \tag{13'}$$

Next, we use the well-known computational correlation for the diffusion coefficient of small particles in gases depending on their size [8]. In comparison with initial expression (6), this correlation can be written in the form:

$$D_r = DB \left(\frac{\lambda}{r_a} \right) = \frac{kT}{6\pi\mu r_a} \left[1 + B \left(\frac{\lambda}{r_a} \right) \right] , \tag{14}$$

$$B \left(\frac{\lambda}{r_a} \right) = \frac{\lambda}{r_a} \left[a + b \exp \left(- c \frac{r_a}{\lambda} \right) \right] , \tag{14'}$$

where λ is the free path of the gas molecules; $B(\lambda/r_a)$ is a correlation function that allows for the size of particles in their ratio with λ; the empirical coefficients a, b, and c are equal to 1.25, 1.42, and 0.87, respectively.

Expressing the mass of the particles as $m = 4/3\pi r_a^3 \rho_a$ and substituting Eq. (14), we transform Eq. (13) as

$$\frac{\overline{C}(x)}{C_0} \cong 0.715 \exp\left[-\left[0.166\frac{D(1-\varepsilon)}{VR\varepsilon} + 0.222\frac{r_a^2\rho_a V}{\mu R}\left(1 + F\left(\frac{\lambda}{r_a}\right)\right)\right]\frac{x}{R}\right], \tag{15}$$

Finally, to simplify the formulas for subsequent analysis, we use Eq. (15) to determine the characteristic length (height) of the filtration bed $x = L_e$, over which the initial concentration decreases by a factor of $e = 2.7182$. To simplify the computational formula further with an error admissible for the analysis, we average and take outside the brackets of Eq. (15) the empirical coefficient $A = 0.166 \ldots 0.222 \approx 0.2$:

$$F\left(\frac{\lambda}{r_a}\right) = \frac{\lambda}{r_a}\left[1.25 + 1.42\exp\left(-0.87\frac{r_a}{\lambda}\right)\right].$$

$$L_e \cong 3.3\mu R^2\left[\frac{kT}{\pi V r_a}\left(\frac{1-\varepsilon}{\varepsilon}\right)^2 + r_a^2\rho_a V\left(1 + B\left(\frac{\lambda}{r_a}\right)\right)\right]^{-1}, \tag{16}$$

where for a value of λ on the order of 10^{-8} m we can neglect the correlation function $B(\lambda/r_a)$ in a first approximation and obtain the expression

$$L_e \cong 3.3\mu R^2\left[\frac{kT}{\pi V r_a}\left(\frac{1-\varepsilon}{\varepsilon}\right)^2 + r_a^2\rho_a V\right]^{-1}. \tag{16'}$$

After this, according to the initial definition in the literature [6], the coefficient of filtrational absorption and the percentage of the slipping of aerosol particles in the considered bed of height $x = H$ are expressed by the computational formulas:

$$E = 1 - \frac{C(H)}{C_0} = 1 - \exp\left(-\frac{H}{L_e}\right), \tag{17}$$

$$P = (1 - E)\,100\,\% = \exp\left(-\frac{H}{L_e}\right)100\,\%, \tag{17'}$$

where, according to Eq. (16), the quantity L_e is characterized by a quite sufficient base of parameters for analyzing the filtering ability of the bed at the present stage of the development. We may only note that such an exponential formula for slippage is also typical of fibrous filtering structures [9], though for a filtering layer of very insignificant thickness.

Evaluation and Comparative Analysis of the Solution. In their final form calculations by Eqs. (16)-(17) make it possible to carry out a direct comparison of the solution obtained with the known experimental data of [6] on the absorption of aerosol particles in fine and coarse filters. These are HEPA filters and Petryakov filters for small particles (smaller than 1 μm) and the simplest bulk sand-gravel filters for large particles (above 1 μm). Because of the very thin filtration layers for the former particles (1–2 mm), the comparison is limited here and consists in the analysis of experimental and calculated data by the well-known and typical (for such filters) slippage maximum of the particles of critical radius $r_{cr} = 0.05$–0.1 μm [6]. As a consequence and manifestation of the indicated mechanism of transfer and precipitation of particles, when the diffusional mechanism dominates in the region of $r_a < r_{cr}$ and the inertial-viscous one in the region with $r_a > r_{cr}$, in the critical region of $r_a \approx r_{cr}$ this phenomenon is fully confirmed computationally if Eq. (16) is differentiated with respect to the variable r_a:

TABLE 1. Height of Filtering Bed of RAW Charge (mass of aerosols per 1% of slippage)

Characteristic of the filter bed	Height of the bed, m (r_a, μm)		
	1	5	10
Lump bed of RAW and glass-forming materials (R = 100 mm; ε = 0.5)	$4.6 \cdot 10^4$	$6.4 \cdot 10^3$	$4.6 \cdot 10^2$
Crushed glass-forming charge (R = 10 mm; ε = 0.4)	$0.7 \cdot 10^3$	27.6	7.0
Wood chips and shavings (R = 10 mm; ε = 0.7)	$0.2 \cdot 10^3$	7.5	1.9
Sawdust (R = 3 mm; ε = 0.9)	4.6	0.2	0.05
Macroporous charcoal (r_{ef} = 0.1 mm; ε = 0.7)	0.3	0.1	0.03

$$r_{cr} = \left[\frac{kT}{2\pi\rho_a V^2}\left(\frac{1-\varepsilon}{\varepsilon}\right)^2\right]^{1/3}. \tag{18}$$

With allowance for the high porosity of the ultrafibrous structure of such filters of the order of $\varepsilon = 0.97-0.98$ at $T = 300$ K and at the nominal magnitude of filtration velocity $V = 0.05$ m/sec, the calculation of the extremal value of r_{cr} for particles of mineral ash of density $\rho_a = 1000$ kg/m^3 according to Eq. (18) gives a convincing and easily verifiable result for the same order of particles, i.e., $r_{cr} \approx 0.1$ μm.

We obtain a closer physical similarity when we compare and evaluate Eqs. (16)-(17) in application to less porous bulk granular (sand and small-gravel) coarse filters for trapping larger than 1 μm particles, the parameters and the efficiency of gas purification of which in the notation adopted above can be characterized as [6]: R = 0.2–2 mm; V = 0.1 m/sec; ε = 0.4–0.5; H = 0.15–0.2 m; E = 99–99.8%.

In contrast to the former, such filters are also applicable for filtering hot gases; in application to our conditions at T = 600–700 K, the calculation of the absorption coefficient E for the indicated parameters is also confirmed well in practice: L_e (R = 0.2 mm; r_a = 1 μm) = 0.04 m, E (H = 0.2 m) = 1– exp (–0.2/0.004) = 99.3%.

Next, using relations (16)-(17) as a quite acceptable computational technique, we present in Table 1 certain variants of the computational evaluation of a filtering bed of a charge depending on its height, fractional composition, and porosity. In this case in addition to the RAW itself and the glass-forming components the charge has the simplest filtering additions and filters of the type of wood chips and sawdust. It is assumed here that the dimensions of the lumps of the RAW and glass-forming material are sufficiently large and that the filtration of aerosol occurs only thanks to the indicated additions and fillers. As a separate variant we calculated for comparison the needed height of a RAW charge without such fillers. The temperature and velocity of filtration correspond to the previous comparison of Eqs. (16)-(17) with a bulk coarse filter. In application to the actual disperse composition of wood as a most volatile one when the indicated additions and fillers of the charge are burnt, we included into the calculation particles of size (radius) 1, 5, and 10 μm.

Conclusions. If we satisfy ourselves by the foregoing analysis and comparison of computational formulas (16)-(17) with the characteristics of the familiar fine and coarse filters [6] and adopt the additivity of solution (13), then from all the variants of calculation of the bed height listed in Table 1, actually significant is only the last-mentioned one, at which the calculated height of the filtering bed corresponds to the actual dimensions of the shaft furnace designed for the purpose. A charge bed of approximately the same height of up to 2 m with a wood filler in a RAW charge of about 85–90% in volume was used [5] for experimental investigation of filtration of radioactive aerosols; the escape of radioactivity from the furnace was decreased here precisely to 1–2%. Thus, this approach and the calculated result allow us to rather justifiably approach the technological and design stages of the development.

With all the conventionality of such an estimate, when the indicated filtering fillers do not form a continuous bed, but are localized in the space between the lumps of the RAW and glass-forming charges, the required height of the combined charge can be corrected with allowance for the porosity of the packing of the RAW itself:

$$H' = \frac{H}{1 - \varepsilon_{RAW}} \cong 2H \quad (\varepsilon_{RAW} = 0.5)$$

Here, it is evident that the thus obtained filtration height of gases in a charge should be reckoned from the top of the charge, where the temperature should not exceed 300–400°C, above which (i.e., in the direction to the bed bottom) the wood is subjected to thermolysis and then is burnt. The indicated limit of temperatures is determined separately by thermal calculation of the charge, in which the moisture content of proposed fillers is also of importance. An increased moisture content of wood has a positive effect, as it also creates possibilities and prerequisites for condensational precipitation of aerosols with moisture vapors.

NOTATION

R, radius of lump and filtering elements of the bed; r_{ef}, effective radius of the curvilinear channels for gas flow in the bed; r_a, radius of aerosol particles; r_{cr}, critical radius of particles; m, mass of particles; V, gas flow velocity; f, viscous force of the flow; f_r, radial force of inertia of a particle; C, relative concentration of particles; C_0, initial concentration of particles; j, density of mass flow of particles; D, diffusion coefficient of particles; B, coefficient of Brownian motion of particles; μ, viscosity of the gas medium; T, temperature of the medium; k, Boltzmann constant; L_e, characteristic length (height) of the filtrational bed; x, length (height) of the filtrational bed; H, height of the charge bed; E, filtrational absorption coefficient; P, percentage of slippage; ε, bed porosity.

REFERENCES

1. I. A. Sobolev and L. M. Khomchik, Decontamination of Radioactive Waste at Centralized Stations [in Russian], Moscow (1983).
2. I. A. Sobolev, I. P. Korenkov, L. M. Khomchik, and L. M. Prokazova, Environmental Protection in the Process of Decontamination of Radioactive Waste [in Russian], Moscow (1989).
3. I. A. Sobolev, F. A. Lifanov, S. V. Stefanovskii, et al., Atomn. Énerg. 69, Vyp. 4, 233-236 (1990).
4. S. A. Dmitriev, S. V. Stefanovskii, I. A. Knyazev, and A. L. Mossé, in: Heat- and Mass Transfer in Plasma Apparatuses [in Russian], Minsk (1990), pp. 10-29.
5. S. A. Dmitriev, F. A. Lifanov, I. A. Knyazev, N. N. Buravchenko, and I. A. Sobolev, Atomn. Energ., 70, Vyp. 5, 305-307 (1991).
6. M. I. Birger, A. Yu. Val'dberg, B. I. Myagkov, V. Yu. Padva, A. A. Rusanov, and I. I. Urbakh, Handbook on Dust- and Ash Trapping (ed. by A. A. Rusanov), 2nd rev. edn. [in Russian], Moscow (1983).
7. M. É. Aerov, O. M. Todes, and D. A. Narinskii, Apparatuses with a Fixed Granular Bed: Hydraulic and Thermal Foundations of Operation [in Russian], Leningrad (1979).
8. Yu. M. Shekhtman, Filtration of Slightly Concentrated Suspensions [in Russian], Moscow (1961).
9. N. A. Fuks, A. A. Kirsh, and I. B. Stechkina, Adsorption and Porosity [in Russian], Moscow (1976).