ACOUSTIC COAGULATION OF MOLTEN METAL OXIDE PARTICLES IN A HIGH-TEMPERATURE GAS FLOW

L. D. Buglaeva, V. F. Buryachenko,
I. I. Vernidub, É. M. Timokhin,
A. P. Tishin, B. N. Fedorov,
and G. N. Shustov

UDC 534.541

The coagulation of molten aluminum oxide particles in a high-temperature two-phase medium under the action of sound waves is investigated theoretically and experimentally.

The evolution of the particle-size spectrum of molten metal oxide particles suspended in a high-temperature gas flow in the course of coagulation can be described by the equation [1]

$$\frac{dn(m)}{d\tau} = -n(m)\int_0^\infty K(m,\ m_1)\,n(m_1)\,dm_1 + \frac{1}{2}\int_0^m K(m-m_2,\ m_2)\,n(m-m_2)\,n(m_2)\,dm_2.$$

The first term on the right-hand side of the equation accounts for the decrease in the number of particles of mass m as a result of coagulation with other particles, and the second term characterizes the increase in the number of these particles due to their formation from smaller particles.

Four kinds of particle interaction are customarily distinguished in acoustic coagulation: 1) orthokinetic; 2) pulsation; 3) parakinetic; 4) attraction.

Orthokinetic interaction is the principal type involved in the acoustic coagulation process. The other three interactions only slightly affect the aggregation of particles and can therefore be disregarded in the coagulation calculations. The orthokinetic coagulation mechanism is discussed in detail in [2]. Below, we give the relations from that work to be used in our calculations.

The collision of two vibrating particles is possible when the one having the smaller diameter d_1 enters the "aggregation space" of the larger particle of diameter d_2. The aggregation space is a cylinder, the base diameter of which is equal to the sum of the two particle diameters:

$$d_R = d_1 + d_2,$$

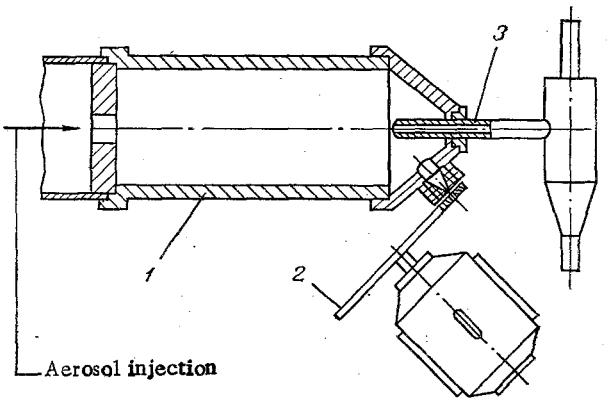

Fig. 1. Experimental arrangement.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 41, No. 2, pp. 239-244, August, 1981. Original article submitted June 23, 1980.

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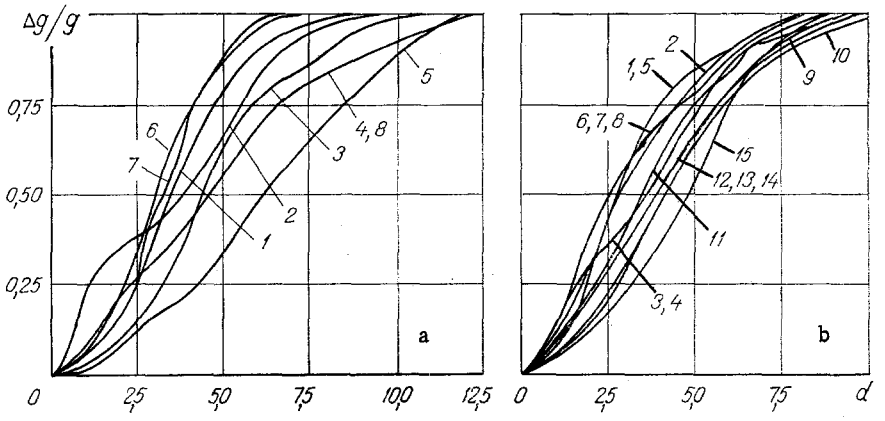

Fig. 2. Integral mass-diameter (d, μm) distribution functions of particles for mixtures containing different quantities of aluminum oxide particles by mass: a) 28%; b) 34%.

while the height is equal to twice the difference between the vibrational displacement amplitudes of the particles:

$$h_R = 2(A_{p_1} - A_{p_2}) = 2\mu_{12}A_g.$$

In this case the constant of the orthokinetic mechanism of particle coagulation as a result of vibratory motion can be written in the form

$$K(m, m_1) = E\pi d_R^2 \mu_{12} A_g f = E\mu_{12} d_R^2 u_g,$$

where

$$\mu_{12} = \frac{u_{12}}{u_g} = \sqrt{\mu_{p_1}^2 + \mu_{p_2}^2 - 2\mu_{p_1}\mu_{p_2}(\mu_{p_1}\mu_{p_2} + \mu_{g_1}\mu_{g_2})};$$

$$\mu_p = \frac{1}{\sqrt{1 + (2\pi\tau_p f)^2}}; \quad \mu_g = \frac{u_{gp}}{u_g}.$$

The coefficients μ_g and μ_p are joined by the relation

$$\mu_g^2 + \mu_p^2 = 1.$$

The particle relaxation time is

$$\tau_p = \frac{\rho_p d^2}{18\eta}\left[1 + A\frac{2l}{d} + Q\frac{2l}{d}\exp\left(-\frac{bd}{2l}\right)\right].$$

In this expression the constants have the values A = 1.246; Q = 0.42; b = 0.87.

The capture coefficient E takes into account the hydrodynamic interaction of the particles as they approach one another. The capture coefficient is interpreted as the ratio of the number of actual collisions to the number of collisions possible in the absence of hydrodynamic interaction.

For particles subjected to the action of a sound field the capture coefficient loses its customary significance. In this case the particles approach and diverge with a variable

TABLE 1. Particle Diameter versus Pressure Amplitude

№	P_g, bar	τ, msec	d_{43}, μm
1	0,1	25	3,9
2	0,45		4,7
3	0,55		4,8
4	1,0		5,1
5	1,5		5,8
6	0,2	15	3,2
7	0,25		3,2
8	1,0		4,8

TABLE 2. Particle Diameter versus Frequency and Pressure Amplitude

№	f, Hz	P_g, bar	d_{43}, μm
	τ=5 msec		
1	1500	0,07	3,25
2	1000	0,2	3,6
3	1600	0,3	3,47
	τ=15 msec		
4	1300	0,05	3,52
5	2000	0,06	3,7
6	150	0,5	3,55
7	200	1,0	3,52
8	250	1,0	3,3
9	600	1,6	3,8
10	800	0,35	4,6
11	1000	1,3	3,95
12	1200	0,6	4,3
13	1400	0,55	4,25
14	1750	1,2	4,45
15	2000	1,2	5,02

velocity due to the vibrations of the medium with the simultaneous occurrence of approach processes associated with other mechanisms of interaction of the particles and the medium. A mathematical solution of the problem of the capture coefficient for the given case has not been obtained to date. Hydrodynamic interaction is approximately included in the calculations according to the Langmuir equation [2]

$$E_L = \left(1 + \frac{0.75 \ln 2k}{k - k_{cr}}\right)^{-2}; \; k = 2u_{12}\tau_2/d_1.$$

On the basis of the engagement effect, the capture coefficient is

$$E = (\sqrt{E_L} + d_{2re})^2; \; d_{2re} = d_2/d_1.$$

The coagulation constant and capture coefficient are calculated from the average particle approach velocity, which is equal to its amplitude value divided by $\sqrt{2}$. The parameters of the aerosol mixture used in the calculations are consistent with their experimental values: $T_k = 3200°K$, $P_k = 45$ bar, $\rho_p = 2200$ kg/m^3, $R_o = 328$ J/kg·K, $\gamma = 1.18$, $\eta = 0.8 \cdot 10^{-4}$ N·sec/m.

The initial particle diameter d_{43} is taken equal to 3.2 μm, and the distribution function corresponds to the particle-size distribution in the gas generator.

The experiments were carried out on an apparatus (Fig. 1) consisting of: a cylindrical chamber 1, in which the mixture is irradiated with sound; a reverse-flow siren 2, which comprises a perforated disk, reduction gear, and electric motor; and a particle sample-taking device 3. The injection of the two-phase mixture is shown in the figure.

The mixture flows out of the chamber through a nozzle port. The perforated disk is set up in a plane parallel to the orifice of the sonic nozzle, with a nozzle-disk spacing of 0.5-1 mm. As the disk spins, the nozzle exit section is periodically closed off, so that waves are transmitted into the chamber. The amplitude and frequency of the waves are varied by changing the spacing between the disk and nozzle orifice as well as the rpm of the disk. The apparatus is so constructed that length of the cylindrical chamber and, hence, the residence time of the mixture in the chamber can be varied by means of additional ring inserts.

The device for sampling the mixture comprises a scoop and a cyclone. The scoop is made in the form of a tube, and helium is fed into its interior for cooling of the mixture. The cooled particles are precipitated in the cyclone. In a special series of experiments we chose the sampling conditions, i.e., the scoop entry velocity and amount of injected helium, to ensure that the extracted samples would be representative. One sample is extracted for a period of 1 sec. The sample is prepared by filtering out the condensed phase from an acetate solution formed in the cyclone; it is then dried in a drying oven. Particle-size analysis is performed under a microscope. A droplet of a suspension of particles in alcohol is deposited on a slide and is then spread over the surface by means of a second slide.

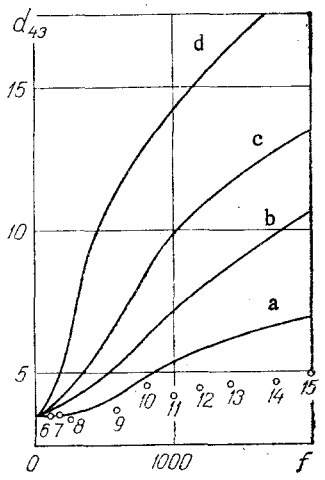

Fig. 3. Calculated and experimental results of acoustic particle coagulation (f, Hz). a) P_g = 0.2 bar; b) 0.4; c) 0.8; d) 1.2 bar.

This breaks up any particle agglomerates, a few of which are present among the sampled particles.

The frequency and amplitude of the sound waves are measured with a piezoelectric pressure-fluctuation probe. The probe signal is recorded from the screen of a cathode-ray oscilloscope on motion-picture film by means of a camera with the framing mechanism removed. The average pressure in the chamber is measured by means of a strain gauge and is recorded on a loop oscillograph. The maximum measurement errors are 12% for the wave amplitude, 1% for the frequency, 1% for the average pressure, and 10-15% for the particle fractional composition.

The experimental procedure essentially entailed comparing the results of the particle-size analysis of aluminum oxide particle samples extracted in tests without sound irradiation and the results obtained for various parameters of the sound field in the chamber.

In the first series of experiments the aerosol mixture contained 28% aluminum oxide particles by mass. The pressure in the chamber was maintained at the 45-bar level. The chambers used in the experiments had mixture residence times τ = 15 and 25 msec. The results of the experiments are summarized in Table 1.

The integral mass-diameter distribution functions of the particles are plotted in Fig. 2a according to the results of the particle-size analysis. The curves are numbered in accordance with the numbering in Table 1.

In this series of experiments oscillations with a frequency of $\sim$2000 Hz were recorded in the chamber. The amplitude decreased somewhat during operation of the apparatus. Clearly, the variation of the acoustical parameters during operation was caused by erosion of the end of the nozzle facing the disk and, as a result, enlargement of the spacing between the nozzle and disk and a decrease in the intensity of the transmitted sound waves. The amplitude values given in Table 1 are averaged over the particle sampling period.

The second series of experiments was carried out with a high-temperature mixture containing $\sim$34% aluminum oxide particles by mass. Heat erosion of the nozzle tip was eliminated by replacing the copper fitting with a molybdenum one. In this case it was possible to excite waves having a desired spectrum of frequencies and amplitudes. The pressure in the chamber was maintained at the 45-bar level. The results of the particle-size analysis are given in Table 2. The integral weight distribution functions are shown in Fig. 2b.

The average diameter d_{43} of the particles formed in the gas generator is d_{43} = 3.2-3.5 μm, and the particle-size distribution function for these particles practically coincides with the distribution curves 6 and 7 in Fig. 2a or curves 1, 4, and 5 in Fig. 2b. It is evident from the data in Table 2 that the particle diameter does not change in the chamber for pressure amplitudes up to P_g = 0.2 bar in the investigated frequency range or for stronger oscillations with amplitudes of up to 1.6 bar at frequencies up to and including 500 Hz. For amplitudes greater than 0.2 bar and frequencies higher than 500 Hz the increase in the particle diameters is appreciable. Figure 3 gives the results of calculations of acoustic particle coagulation according to the analytical procedure described above. The initial particle-size distribution function used in the calculations is the same as in the gas

generator. The particle concentration by mass is ∿34%. The particle residence time in the chamber is $\tau = 15$ msec. The analytical results are qualitatively consistent with the experimental. The growth of the particles becomes appreciable for amplitudes greater than 0.2 bar and at frequencies higher than 500 Hz. It is readily perceived, however, that in comparison with the calculations the experimentally determined aggregation of the particles is considerably less. The discrepancy is probably attributable to overestimated values used in the calculations for the capture coefficient E and relative-velocity factor μ_{12}.

NOTATION

m, particle mass; d_i, particle diameter; $K(m, m_1)$ coagulation constant, equal to the average number of collisions per unit time in unit volume between particles of mass m and m_1, reduced to two particles with those masses; n(m), number density distribution of particles by mass; A_g, displacement amplitude of medium; A_p, particle displacement amplitude; f, sound frequency; u_g, velocity amplitude of medium; u_{gp}, relative velocity amplitude of particles and medium; μ_{12}, relative velocity factor, equal to ratio of maximum difference in particle oscillatory velocities to velocity amplitude of medium; μ_p, entrainment factor (particles by the medium); μ_g, slip factor, equal to ratio of flow velocity around particles to velocity amplitude of medium; η, dynamic viscosity coefficient of medium; ρ_p, material density of particle; l, mean free path of gas molecules; T_k, temperature of medium; P_k, pressure of medium; R_o, gas constant; γ, isentropy exponent; P_g, pressure amplitude; E, capture coefficient; E_L, Langmuir hydrodynamic interaction coefficient; k, small-particle coefficient of inertia; k_{cr}, critical value of coefficient of inertia; τ_p, particle relaxation time; τ, residence time of mixture in chamber; $\Delta g/g$, mass fraction of particles with diameters smaller than d_i relative to mass of particles of all sizes from minimum diameter d_{min} to maximum diameter d_{max}; d_{43}, average particle diameter;

$$\Delta g/g = (\Sigma_{d_{min}}^{d_i} d_i^3 n_i)/(\Sigma_{d_{min}}^{d_{max}} d_i^3 n_i); \quad d_{43} = (\Sigma_{d_{min}}^{d_{max}} d_i^4 n_i)/(\Sigma_{d_{min}}^{d_{max}} d_i^3 n_i).$$

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