Journal of Engineering Physics and Thermophysics, Vol. 71, No. 5, 1998

FREE-EFFLUX VELOCITY OF A LOOSE MATERIAL IN AN ELECTRIC FIELD

A. I. Tsaturyan*

UDC 537.27/29:681.123

Analytical formulas are obtained for description of the behavior of the free-efflux velocity and flow rate of a loose material under the action of an electric field. Experimental data are presented and compared with calculations for a slot electrode feeder.

Storage, transport, and processing of loose materials are among the most wide-spread technological operations involved in the entire production process. It should be noted that in many cases free efflux of loose materials is the main component of more complicated operational processes and is of key importance for the quality of the final product.

The mass flow rate of outflowing loose material can be controlled by changing its flow velocity through the outlet or the size of the outlet. In the first case various kinds of agitators [1], such as mechanical, vibrational, aeration, etc., are used. The second procedure is more widely used and is implemented with the aid of rather simple devices called gravity freeders [1]. When the outlet is smaller than a certain largest size determined from the condition of bridging, the efflux is stopped. In the flow preceding bridging, the flow rate is stable and minimum for specified concrete conditions. Mass flow rates lower than this minimum flow rate are called flow microrates [1].

Expansion of the range of control of the flow rate of the free efflux by changing the shape of the outlet or its cross section usually covers the upper limit, i.e., high flow rates, and is useless for flow microrates. In the case of flow microrates out of an outlet with a fixed cross section, the flow rate can be controlled using a nongravity agitator, for example, an electric field [2].

When an electric field is applied to a loose material, its particles are polarized and additional forces caused by this polarization change the fluidity of the material. Consequently, an electric field can be used as a convenient means for a short-duration and reversible change in the mechanical properties of loose dielectric materials in concrete technological processes.

In what follows we discuss quantitative characteristics of the effect of an electric field on the free-efflux velocity of a loose material out of an outlet with a fixed cross section.

The average velocity of the vertical efflux of the material over the outlet is described quite well by the relation [3]

$$v = \lambda \sqrt{\left(2g\left(2.1\frac{s}{p} - 3.4\frac{\tau_0}{g\rho}\right)\right)}\,. \quad (1)$$

The initial shear strength is determined from the formula [3]

$$\tau_0 = \frac{a_0 b_0 \rho g}{3.2\,(a_0 + b_0)}\,. \quad (2)$$

* Deceased.

State Engineering University of Armenia, Erevan, Armenia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 71, No. 5, pp. 795-798, September-October, 1998. Original article submitted January 22, 1997; revision submitted December 16, 1997.

The efflux coefficient λ varies from 0.2 to 0.65 for different loose materials, and high coefficients are found for dry granular highly loose materials (for example, dried river sand) and low ones, for moist bound materials.

Within the mechanical theory of an electric field the effect of the field on a loose material can be reduced to growth of normal and shear stresses, and in this case their maximum increase is numerically equal to the average bulk density w of the electric-field energy [4]. Consequently, by analogy with (1), the efflux velocity of a loose material in an electric field can be described by the formula

$$v_e = \lambda \sqrt{\left(2g\left(2.1\frac{s}{p} - 3.4\frac{\tau_0 + w}{g\rho}\right)\right)} . \tag{3}$$

When the flow rate of a loose material is controlled by an electric field, its bulk density changes in the efflux region. However, above the continuously destroyed bridges the material remains loose [1]. In this case the volume concentration of the particles lies in the range $\vartheta = 0.52-0.74$ [5]. Operating the efflux velocity averaged over the cross section of the outlet and, to a rough approximation, assuming constancy of the bulk density during the efflux, for the mass flow rate of the loose material we obtain

$$Q_e = \lambda\rho s \sqrt{\left(4.2g\frac{s}{p} - 6.8\frac{\tau_0 + w}{\rho}\right)} . \tag{4}$$

At a certain density w_p of the electric-field energy, the loose material is transformed into a pseudosolid state, and the free efflux is choked. This energy density is determined from (4) for the condition $Q_e = 0$, and at $\vartheta = 0.52$ it is equal to

$$w_p = 0.62\,\rho g\frac{s}{p} - \tau_0 . \tag{5}$$

In a dc electric field, the energy density in the bulk of spherical particles of concentration $\vartheta < 0.7$ whose conductivity is much higher than the conductivity of air can be expressed by the relation [4]

$$w = 9\frac{\vartheta\,\varepsilon_0}{(1-\vartheta)^2}E^2 , \tag{6}$$

where $\varepsilon_0 = 8.85\cdot 10^{-12}$ F/m.

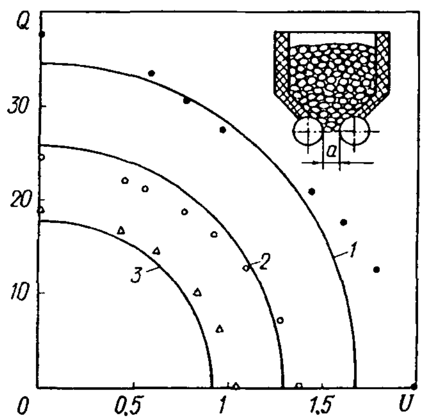
In the region of formation of the free efflux of the loose material, it is intensely loosened due to a sharp decrease in the internal-friction coefficient. In the formula for the free-efflux velocity, this phenomenon in taken into consideration by the efflux coefficient λ. The same quantitative characteristic can be assigned to the volume concentration, and in (6) $\lambda\vartheta$ can be substituted for ϑ.

For an electrode system of parallel cylinders whose diameters are much larger than the width of the slot, the electric field in the slot can be assumed to be uniform and its average strength can be used:

$$E = \frac{U}{a} . \tag{7}$$

For evaluation of the volume concentration ϑ of the loose material the following fact will be taken into account. The least volume concentration of the particles of the loose material at rest corresponds to a simple cubic arrangement of the particles. It is evident that motion of the material is accompanied by its loosening, and the packing density of the particles cannot be higher than the density corresponding to their cubic arrangement. Consequently, $\vartheta = 0.52$ can be assumed [5], and then

$$w = 62\cdot 10^{-12}\frac{U^2}{a^2} . \tag{8}$$



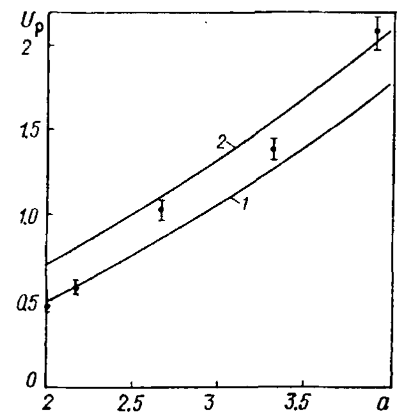


Fig. 1. Flow-rate characteristics of an electrode feeder for different interelectrode distances (slots): 1) $a = 3.9$ mm, 2) 3.3, 3) 2.6 mm. Q, g/sec; U, kV.

Fig. 2. Plot of the choke voltage of loose-material efflux U_p versus the size of the interelectrode distance (slot) a: 1) $\tau_0 = 4.35$ Pa, 2) 0. U_p, kV; a, mm.

In the case of chocked efflux of the loose material, on the basis of (5) and (8) we can write

$$U_p = 10^5 a \sqrt{\left(\rho g \frac{s}{p} - 1.6\,\tau_0\right)} . \qquad (9)$$

Substitution of (8) into (4) gives the flow-rate characteristic of the free efflux of the loose material in the electric field:

$$Q_e = \lambda \rho s \sqrt{\left(4.2 g \frac{s}{p} - 6.8 \frac{1}{\rho}\left(\tau_0 + 62 \cdot 10^{-12} \frac{U^2}{a^2}\right)\right)} . \qquad (10)$$

The characteristics for the limiting cases can be obtained from (10): in the case of no electric field $U = 0$ and

$$Q = \lambda \rho s \sqrt{\left(4.2 g \frac{s}{p} - 6.8 \frac{1}{\rho} \tau_0\right)} ; \qquad (11)$$

in the case of a choked free efflux $Q_e = 0$ and the choking voltage is described by expression (9).

In relative units with account for (9) and (11), flow characteristic (10) is expressed by the formula

$$Q_* = \sqrt{1 - U_*^2} , \qquad (12)$$

where $Q_* = Q_e/Q$ and $U_* = U/U_p$.

The relations obtained are used for description of the flow-rate characteristic of an electrode slot feeder (Fig. 1). The feeder has two parallel cylindrical electrodes with a diameter of 12 mm and a length of 40 mm. River sand with a moisture content of 3.9% and a grain size of 0.63–1.00 mm whose bulk density is 1460 kg/m^2 was used as the object of study. For this object the two largest bridging slots were found experimentally, for which the initial shear resistance was calculated from formula (2). Averaging the two values gave $\tau_0 = 4.35$ Pa. Using these data, in the case of a dc electric field, flow-rate characteristics of the feeder considered were calculated from formula (10). Results of the calculation and experimental data for three interelectrode distances are shown in Fig. 1, from which it follows that except for the region preceding choking, the flow-rate characteristic obtained differs from the experimental data by at most 20%. The substantial difference between the calculated results and the experimental data found on the choking threshold can be explained by the fact that in the region of formation of the free-efflux flow, the volume concentration becomes larger than $\lambda\vartheta$ and tends to ϑ. It follows from the results obtained that acceptable agreement of the calculations and the experimental data occurs for $Q_e > (0.3-0.4)Q$.

We have assumed that in the region of flow formation the particle concentration is invariable. Meanwhile, for the loose state it varies in the range 0.52–0.74, and the efflux coefficient varies in the range 0.2–0.65. It is of interest to evaluate the error in this assumption. For the two limiting cases at a = 3.9 mm, the choking voltages calculated following the procedure described are:

$$U_p = 1680 \text{ V} \quad \text{for} \quad \lambda = 0.65 \quad \text{and} \quad \vartheta = 0.52\,; \quad U_p = 2510 \text{ V} \quad \text{for} \quad \lambda = 0.20 \quad \text{and} \quad \vartheta = 0.74\,.$$

A comparison of these data shows that the largest error caused by the assumption of a constant concentration is at most 40%. It should be noted that for a = 3.9 mm, the experimental choking voltage (1980 V is the dark point on the voltage axis in Fig. 1) lies between these two limiting calculated values.

An important characteristic of the electrode feeder is the relation $U_p(a)$, which allows us to evaluate the actual potentialities of the electric field as a physical factor for controlling the free efflux of loose materials. It follows from the results shown in Fig. 2 that the theoretical curve $U_p(a)$ is almost linear irrespective of the value of τ_0. The ckoking voltage increases with decreasing τ_0. For ideal (unbound) loose materials the relation $U_p(a)$ is described by curve 2 and almost all the experimental data lie within this line and curve 1 corresponding to τ_0 = 4.35 Pa.

Thus, on the basis of the obtained quantitative characteristics of the free efflux of loose materials, a formula is obtained to take into consideration the effect of a dc electric field on the flow rate and is verified. Because of a limited amount of experimental data, broad generalization is impossible, and therefore the present procedure can be recommended for evaluation of flow-rate characteristics of slot electrode feeders with a width of the slot of several millimeters in the case of controlled efflux of fine-grained highly loose dielectric materials.

NOTATION

λ, efflux coefficient; g, gravitational acceleration; s and p, cross-sectional area and perimeter of the efflux outlet; ρ and ϑ, bulk density and volume concentration of the loose material; τ_0, initial shear resistance; a_0 and b_0, width and length of the largest bridging slot; w, volume energy density of the electric field; Q, mass flow rate of the loose material; ε_0, electric constant; E, electric-field strength; U, voltage at the electrodes of the feeder; a, interelectrode distance; Q_* and U_*, flow rate and voltage in relative units; v, efflux velocity. Subscripts: *, relative units; p, pseudosolid state corresponding to choked efflux; 0, parameters refering to the largest bridging slot; e, electric field.

REFERENCES

1. B. S. Fialkov, V. T. Plitsyn, and E. V. Maksimov, Control of the Efflux of Loose Materials [in Russian], Alma-Ata (1981).
2. A. I. Tsaturyan, Élektrichestvo, No. 6, 50-52 (1981).
3. R. L. Zenkov, G. P. Grinevich, and V. S. Isaev, Hopper Devices [in Russian], Moscow (1977).
4. A. I. Tsaturyan, Élektrichestvo, No. 10, 40-45 (1985).
5. A. D. Zimon and E. I. Andrianov, Autohesion of Loose Materials [in Russian], Moscow (1978).