GAS-FILM FILTRATION OF FINE-DISPERSE SUSPENSIONS

A. M. Volk, V. A. Bobrovich, and I. M. Plekhov

UDC 66.067.01

Film filtration of fine-disperse suspensions occurring on permeable cylindrical surfaces exposed to a gas flow is studied. The processes without formation of a sediment and those involving its accumulation are considered.

The analysis of investigations into the separation process of fine-disperse suspensions has shown that sufficiently reliable results are found with a combination of experimental and theoretical methods. The most commonly used method for separation of suspensions is filtration whose velocity is described by the experimental Darcy law [1].. Accumulation of a sediment and its packing cause an increase of resistance to the process course, and this requires periodical regeneration of the filtering surface. A rise in pressure increases the filtration velocity but decreases the cycle time.

The method for gas-film filtration of suspensions [2] is rather effective. A gas flow produces overpressure (Fig. 1). The film flow of the suspension occurs in an internal wall of the cylindrical filtering element in the direct-flow regime under the action of gravity and tangential stresses of friction forces arising at the gas–suspension boundary. As a result, conditions are developed which prevent sediment deposition on the permeable surface, thus considerably increasing the cycle time.

Filtration of the graphite–water suspension with solid-phase particles 2-90 μm in size at gas velocities of 8-10 m/sec takes place without formation of sediment [3]. The experimental investigations have shown that with increasing the pressure up to 10 kPa the filtration velocity rises close to a linear law. In this case there is no essential change in the sediment resistance. A further increase in the pressure causes accumulation of the sediment and decreases the process efficiency.

The rise of the mean-flow-rate gas velocity and of the suspension flow rate leads to reduction of the filtration velocity. Due to the liquid phase outflow a decrease in the volumetric flow rate of the suspension occurs on the 2 m long permeable element and the local filtration velocity increases by 2-3 times. The separation process depends both on the physicochemical properties of the suspension and on the hydrodynamic characteristics of the flow.

During mathematical simulation of the film flow with introduction of effective viscosity the suspension may be considered as a Newtonian fluid within the limits of the concentration variation up to 0.5 [4]

$$\frac{\mu}{\mu_0} = 1 + 5.5c\,\frac{10 - (84/11)\,c^{2/3} + 4c^{7/3}}{10 - 25c + 25c^{7/3} - 10c^{10/3}}. \tag{1}$$

Let us consider the steady-state axisymmetric flow of a viscous incompressible fluid over the inner wall of the permeable cylinder exposed to the gas flow. Choose a cylindrical system of coordinates r, φ, z. By axisymmetry, $\partial/\partial\varphi \equiv 0$. Write the Navier–Stokes equation for the axial velocity component and that of discontinuity [5] as

$$\rho\left(v\frac{\partial u}{\partial r} + u\frac{\partial u}{\partial z}\right) = \rho g - \frac{\partial P}{\partial z} + \mu\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial z^2}\right), \tag{2}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(rv) + \frac{\partial u}{\partial z} = 0. \tag{3}$$

The liquid phase outflow velocity v_0 on some element Δz of the cylinder is taken to be constant. The volumetric flow rate of the incompressible fluid through cylindrical surfaces of equal length will be the same: $2\pi rv\Delta z = 2\pi Rv_0\Delta z$. Hence we find the radial velocity in the liquid film

S. M. Kirov Belorussian Technological Institute, Minsk. Translated from Inzhenerno-fizicheskii Zhurnal, Vol. 63, No. 6, pp. 702-707, December, 1992. Original article submitted July 8, 1991.

$$v = v_0 R/r. \tag{4}$$

Then from the discontinuity equation (3) we obtain $\partial u/\partial z = 0$ and $u = u(r)$.

Neglecting the capillary forces of the film surface tension, assume that $\partial P/\partial z = 0$ [6]. Equation (2) takes the form

$$\frac{\partial^2 u}{\partial r^2} - \frac{1}{r}\left(\frac{v_0 R}{\nu} - 1\right)\frac{du}{dr} = -\frac{g}{\nu}. \tag{5}$$

The equation under consideration has the general solution

$$u = c_1 r^{\frac{v_0 R}{\nu}} + c_2 + \frac{g}{2(v_0 R - \nu)} r^2. \tag{6}$$

The solution obtained (6) is insufficiently convenient for investigation. If we take into account that in the large-diameter cylinder the radius over the film thickness varies slightly, then we may replace $1/r$ by $1/R$ and transform Eq. (5) to the form

$$\frac{d^2 u}{dr^2} - \left(\frac{v_0}{\nu} - \frac{1}{R}\right)\frac{du}{dr} = -\frac{g}{\nu}.$$

Shifting the origin of the coordinates onto the inner cylinder wall and substituting $r = R - y$, we obtain

$$\frac{d^2 u}{dy^2} + \left(\frac{v_0}{\nu} - \frac{1}{R}\right)\frac{du}{dy} = -\frac{g}{\nu}, \tag{7}$$

then by denoting $\lambda = v_0/\nu - 1/R$, we find the general solution to Eq. (7)

$$u = c_1 \exp(-\lambda y) + c_2 - \frac{g}{\nu} y. \tag{8}$$

Arbitrary constants for solving (8) are determined from the initial conditions

$$U = 0 \text{ at } y = 0; \quad \mu \frac{du}{dy} = \sigma \text{ at } y = \delta.$$

In this case we have

$$u = \left(\frac{\sigma}{\mu} + \frac{g}{\lambda\nu}\right)\frac{1}{\lambda}\exp(\lambda\delta)[1 - \exp(-\lambda y)] - \frac{g}{\nu} y. \tag{9}$$

By integrating the axial velocity component (9) with respect to the film thickness, it is possible to define the volumetric flow rate per perimeter unit

$$Q = \int_0^\delta u\,dy = \left(\frac{\sigma}{\mu} + \frac{g}{\lambda\nu}\right)\frac{1}{\lambda^2}[(\lambda\delta - 1)\exp(\lambda\delta) + 1] - \frac{g\delta^2}{2\lambda\nu}. \tag{10}$$

The change in the volumetric flow rate over the permeable cylinder length is found by the local liquid phase outflow velocity

$$\frac{dQ}{dz} = -v_0 \quad (v_0 > 0). \tag{11}$$

From the material balance equation for the solid phase $(c+dc)(Q+dQ) = cQ$, confining ourselves by the first-order differentials, we derive

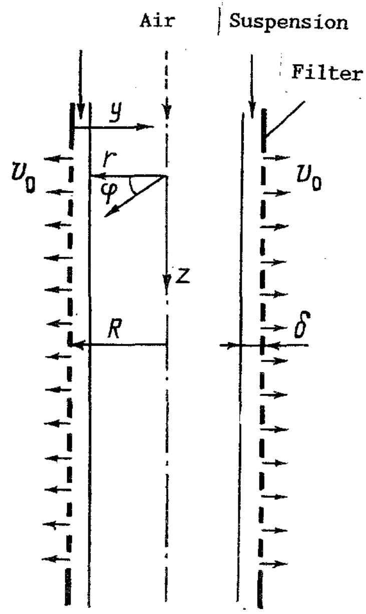

Fig. 1. Diagram of gas-film filtration of a suspension.

$$\frac{dc}{dz} = -\frac{c}{Q}\frac{dQ}{dz} = \frac{cv_0}{Q}. \tag{12}$$

The concentration determines the suspension density: $\rho = \rho_s c + \rho_0(1 - c)$. The gas flow action is transmitted through the surface friction forces. Under the discontinuity condition, the tensors of tangential stresses at the phase interface with account of irregular roughness of the channel walls in the film flow [7] are as follows

$$\sigma = \frac{0,3164}{\mathrm{Re}_g^{0,25}} \frac{\rho_r w^2}{8} \left(1 + 150 \frac{\delta}{R}\right). \tag{13}$$

By generalization of the experimental investigations and of the calculations performed by the derived mathematical model (1), (10)-(13) on the basis of the Darcy law, we found the relation for determining the local liquid phase outflow velocity

$$v_0 = \gamma \frac{\Delta P}{\mu(R_{fs} + R_s)} = \frac{\Delta P\left[1 - \exp\left(-m\sqrt{\Delta P/(\rho\langle u\rangle^2)}\right)\right]}{\mu(R_{fs} + Ac)}. \tag{14}$$

The effect of the flow on the hydrodynamics process is taken into account by the filtration coefficient γ, which depends on the wall pressure drop-to-velocity film head ratio [8]. From a comparison between the calculations made by relations (1), (10)-(14) and the experimental data we determined that m = 0.2.

The resistance of the filtration baffle and of the thin sediment bed (formed when filling all the roughnesses) depends both on the permeable surface structure and on the physicochemical properties of the suspension solid phase. Given in Table 1 are the resistances of the investigated materials obtained by experimentation. During filtration of the graphite–water suspension with the dimension of the solid phase particles 2-90 μm in size, we obtained the coefficient $A = 4.3 \times 10^{10}$ m^{-1} for the sediment resistance. Filtration was carried out at a mean-flow-rate gas velocity 9 m/sec and excess pressure 7.5 kPa. The length of the permeable cylindrical element was 2 m. The original volumetric flow rate of the suspension was selected in such a way that the concentration varied from $c_0 = 0.05$ at the inlet up to $c = 0.5$ at the outlet. And in doing so the sediment accumulation was not observed. The calculation was performed using a step-by-step method. The variation step of length Δz was taken so that with its reduction by two times and repeated recalculation, the changing values coincided with the prescribed accuracy.

TABLE 1. Resistance of Filtering Materials

Material	Cloth	Knitted fabric	Needle-penetrating felt	Chlorine	Lavsan silk	Metal ceramics
$R_{fs}\cdot 10^{10}$ m^{-1}	1,7	3,5	4	4,5	5,7	7

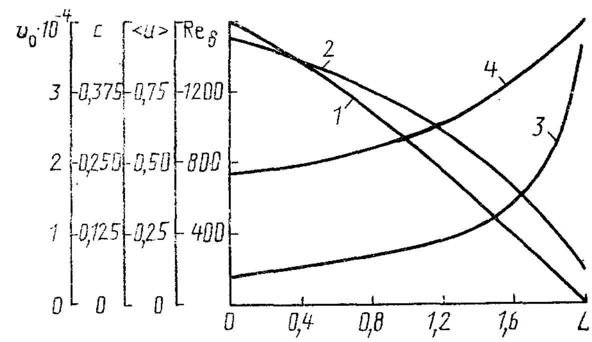

Fig. 2. Change in characteristics of the film flow of the graphite–water suspension over the filter length (at ΔP = 7.5 kPa, w = 9 m/sec): 1) Re_δ ; 2) $\langle u \rangle$ (m/sec); 3) c; 4) v_0 (m/sec).

The results of the computations made by formulas (1), (10)-(14) are presented in Fig. 2. The concentration of the suspension and its rheological properties essentially vary only at the finite filter section. The profile of the axial velocity component (9) is characterized by a large gradient on the permeable surface (Fig. 3). The axial velocity component (9) at a distance 2 μm from the surface is more than one order higher than the radial one (4), thus providing the hydrodynamic wash-out of particles having a rather small dimension. Investigation of the samples of the operating filters under the microscope shows that only filling of surface roughnesses by the filtering suspension sediment occurs.

The studies performed show the stable operation of the filter within the limits of the volumetric flow rate of the suspension to Re_δ = 1600. The liquid phase outflow decreases the degree of turbulence and stabilizes the film flow [5]. The mean outflow velocity on the filtering surface is $v = 2.6 \times 10^{-4}$ m/sec, which is 5-10 times higher than in a centrifugal filter-thickener or in a disk vacuum-filter. In addition, the filtrate purity is two orders higher. The instrumental-technical implementation of the gas-film filtration allows us to decrease the specific metal capacity by not less than two times as compared with other methods.

At volumetric suspension flow rates to Re_δ = 400 and gas velocities to 4 m/sec the gas-film filtration of the graphite–water suspension with solid-phase particles of size 2-25 μm takes place with accumulation of the sediment. In this connection we investigated certain ways for regeneration of the filtering surface: backwashing, short-term interruption of the gas flow supply, and shaking up.

The most preferable method is regeneration of the filter by short-term (by 2-6 sec) interruption of the gas flow supply [9]. This makes it possible to accomplish the process steadily under the self-regeneration conditions. Deformation of the filtering element leads to destruction of the sediment and to its wash-out by the suspension flow. In this case a sufficiently high regeneration degree is achieved, which remains practically constant from cycle to cycle.

The experimental investigations have shown (Fig. 4) that the change in the resistance of the filtering element, together with the accumulated sediment bed during the cycle, is described by the differential equation

$$\frac{dR_f}{d\tau} = kR_f .$$

Upon integrating, we derive

$$R_f = R_0 \exp(k\tau).$$

TABLE 2. Characteristic of the Filtration Process with Sediment Accumulation at $v_f^{min} = 5.56 \times 10^{-5}$ m/sec; $\Delta P = 3$ kPa; $w = 1.5$ m/sec; $c_0 = 0.05$; $L = 2$ m

Method of regeneration	$R_0 \cdot 10^{10}$, m^{-1}	k	$\tau_{max} \cdot 3600$, sec	$\langle v_f \rangle \cdot 10^{-5}$, m/sec	Re_δ
Washing	2,13	0,062	15,00	9,20	285—110
Short-term interruption of gas supply	3,10	0,107	5,16	7,42	195—110
Shaking up after drying	3,39	0,152	3,06	7,07	180—110

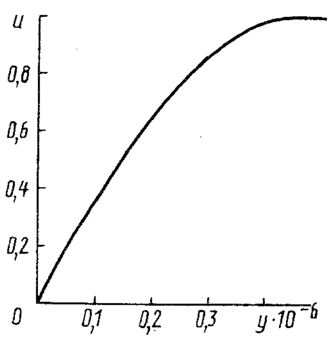

Fig. 3

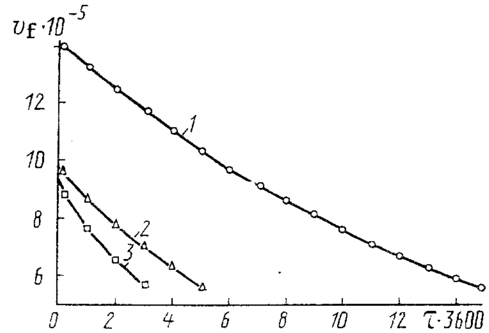

Fig. 4

Fig. 3. Change of the axial velocity component in the suspension film (at $Re_\delta = 920$).

Fig. 4. Change in the suspension filtration velocity (15) during the interregeneration period (Table 2): 1) washing; 2) short-term interruption of gas supply; 3) shaking after drying.

Then the mean liquid phase outflow velocity on the permeable surface takes the form

$$v_f = \frac{\Delta P}{\mu R_0 \exp(k\tau)}. \quad (15)$$

At the initial time instant the outflow velocity will be maximum $v_f^{max} = v_f(0)$. Assigning the minimal outflow velocity v_f^{min}, we determine the cycle duration

$$\tau_{max} = \frac{1}{k} \ln\left(\frac{\Delta P}{\mu R_0 v_f^{min}}\right).$$

Filters with sediment wash-out are economically suitable when $v_f^{min} = 5.56 \times 10^{-5}$ m/sec [10]. The mean filtration velocity during the cycle is as follows:

$$\langle v_f \rangle = \frac{1}{\tau_{max}} \int_0^{\tau_{max}} v_f d\tau = \frac{v_f^{max} - v_f^{min}}{k\tau_{max}}.$$

In Table 2 are tabulated the calculated characteristics of the gas-film filtration through the knitted fabric of the graphite—water suspension with the dimension of the solid phase particles 2-25 μm. The resistance of the filtration surface R_0 after regeneration and the order k of the variation in the resistance were defined from the experimental data (Fig. 4) on the basis of relation (15).

The mathematical simulation of the gas-film filtration of the fine-disperse suspensions enables us to calculate the characteristics of the process, to increase its efficiency, and to obtain the outlet product of the required concentration.

NOTATION

A, coefficient of sediment resistance; c_0, c, initial and current volumetric concentrations; c_1, c_2, arbitrary constants; g, free fall acceleration; k, coefficient expressing the order of the variation process in the filter resistance; L, R, length and radius of the cylindrical filtering element; m, coefficient; P, pressure; Q, volumetric flow rate of the suspension per perimeter unit; r, φ, z, cylindrical coordinates; R_0, R_f, resistances of the filtering element together with the sediment bed at the cycle beginning and during filtration; R_{fs}, filtering surface resistance; R_s, resistance of the suspension sediment bed; u, v, axial and radial velocity components in a liquid film; v_0, v_f, local and mean velocities of liquid phase outflow on the filtering surface; v_f^{max}, v_f^{min}, $\langle v_f \rangle$, maximal, minimal, and mean filtration velocities at the cycle period; w, mean-flow-rate gas velocity; y, distance from the filtering surface; γ, filtration coefficient taking into account the flow hydrodynamics; Δ, increment; δ, film thickness; λ, coefficient; μ_g, μ_0, μ, coefficients of dynamic viscosity of gas, liquid phase, and suspension, respectively; ν, coefficient of the kinematic suspension viscosity; ρ_g, ρ_0, ρ_s, ρ, densities of gas, liquid phase, solid particles, and suspension, respectively; τ, time; τ_{max}, cycle time; σ, tangential stresses at the gas–suspension flow interface; $Re_g = \rho_g w 2R/\mu_g$, Reynolds number for gas; $Re_\delta = 4Q/\nu$, Reynolds number for the suspension film.

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