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OPTIMAL HORIZONTAL PNEUMATIC TRANSPORT

V. V. Kazantsev and M. B. Rivkin

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A study has been made of the effects of periodic large-scale pressure perturbations on the passage of air through a moving bed of granular material in dense-phase horizontal pneumatic transport.

Experiment shows [1] that horizontal pneumatic transport allows the throughput to be increased by increasing the air speed up to some limit, after which an adverse effect sets in, which cannot be explained in terms of existing views on the mechanism of motion in high-concentration two-phase mixtures, according to which the mixing in the lower layer of material (bed) occurs on account of the tangential stresses proportional to the air speed acting at the phase interface [2]. Also, this model fails to explain the very considerable pressure fluctuations accompanying the motion of the mixture through the pipeline (Fig. 1).

The studies on the structure of high-concentration flows [3] provide the following model for the transport; most of the material is transported in the lower part of the pipeline at a constant porosity m_0 as a bed whose height and structure vary little along the length [2]. Ridges or dunes travel along the upper surface of the bed [4], and the air flowing over these gives rise to periodic pressure perturbations, which interact with the air flowing through the bed. This in turn gives rise to an oscillating force within the bed, which is directed along the line of flow and tends to accelerate the bed.

As the frequency of ridge passage is a single-valued function of the air speed, we have to examine the transient-state passage of the air through the bed for a fixed porosity in response to two forces: a constant pressure gradient and a periodic pressure perturbation at the upper boundary.

The following is [5] the linearized equation for isothermal infiltration:

$$\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial z^2} - M \frac{\partial P}{\partial t} = 0, \tag{1}$$

$$0 < x < L,\quad 0 < z < H,\quad t > 0,\quad M = \varepsilon m_0/kp_0,\quad P = p^2.$$

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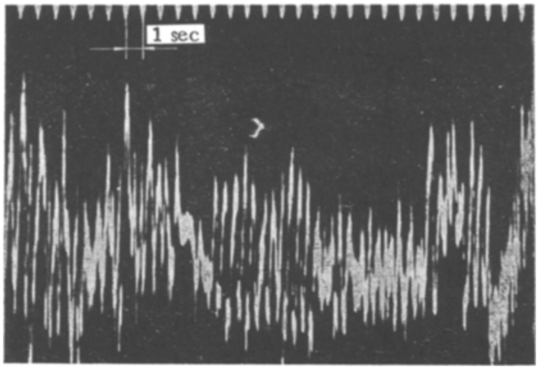

Fig. 1. Characteristic pressure-pulsation oscillogram for a transport pipeline; D = $2.1 \cdot 10^{-2}$ m, L = 14 m, material alumina.

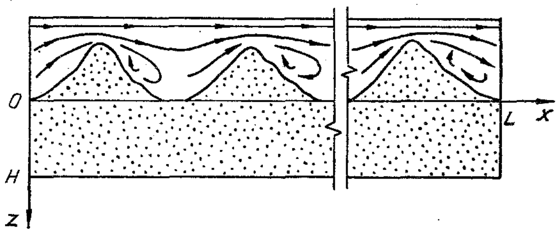

Fig. 2. Calculation scheme.

The boundary conditions are

$$P(0,\ x,\ t) = [p_0 + p_e(1 - x/L) + p_d(x - vt)]^2, \tag{2}$$

$$\frac{\partial}{\partial z} P(H,\ x,\ t) = 0, \quad 0 \leqslant x \leqslant L, \tag{3}$$

where $p_d(x-vt)$ is a periodic perturbation of given form moving with a speed v with respect to the bed, and

$$P(z,\ 0,\ t) = (p_0 + p_e)^2, \tag{4}$$

$$P(z,\ L,\ t) = p_0^2, \quad 0 \leqslant z \leqslant H. \tag{5}$$

The initial condition is

$$P(x,\ z,\ 0) = p_0^2,\ 0 < x < L, \quad 0 < z < H. \tag{6}$$

Equations (1)-(6) may be solved by finite integral transformation [6]; the solution is sought in the form

$$P = \frac{4}{HL} \sum_{n=0}^{\infty} \left[\sum_{m=1}^{\infty} P_{nm}(t) \sin \lambda_m^{0.5} x \right] \sin \nu_n^{0.5} z, \tag{7}$$

where

$$\lambda_m = \frac{\pi^2 m^2}{L^2}; \quad m = 1,\ 2, \ldots, \infty, \tag{8}$$

$$\nu_n = \frac{\pi^2 (2n+1)^2}{4H^2}; \ n = 0,\ 1,\ 2,\ \ldots, \infty. \tag{9}$$

$P_{nm}(t)$ is defined by the following:

$$M \frac{d}{dt} P_{nm}(t) + (\nu_n + \lambda_m) P_{nm}(t) = \Phi_{nm}(t) + \Psi_{nm} \tag{10}$$

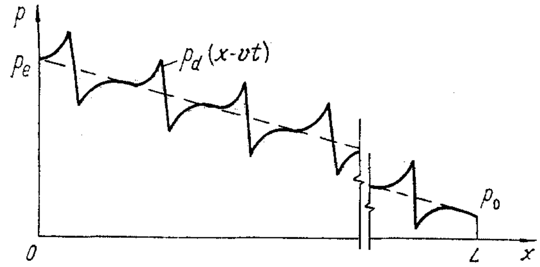

Fig. 3. Pressure distribution along a transport pipeline.

and satisfies the initial condition

$$P_{nm}(0) = \frac{P_0}{(\nu_n\lambda_m)^{0.5}}, \tag{11}$$

where

$$\Psi_{nm} = \left(\frac{\lambda_m}{\nu_n}\right)^{0.5} [(p_0 + p_e)^2 - (-1)^m p_0^2]; \tag{12}$$

$$\Phi_{nm}(t) = (\nu_n)^{0.5} \int_0^L [p_0 + p_e(1 - x/L) + p_d(x - vt)]^2 \sin \lambda_m^{0.5} x dx. \tag{13}$$

We represent the periodic perturbation (Figs. 2 and 3) as a Fourier sine series:

$$p_d(x - vt) = \sum_{k=1}^{\infty} b_k \sin k\omega_0 (x - vt), \tag{14}$$

where ω_0 is the frequency of the pressure fluctuations, which is a single-valued function of the air speed. We have as follows up to terms of the second order of smallness:

$$\Phi_{nm}(t) \simeq \left(\frac{\nu_n}{\lambda_m}\right)^{0.5} p_0^2 + \left(\frac{\nu_n}{\lambda_m}\right)^{0.5} p_e^2 [1 + (-1)^m] + \frac{2p_e^2(\nu_n)^{0.5}}{\lambda_m^{1.5} L^2} \times$$
$$\times [(-1)^m - 1] + 2p_0 p_e \left(\frac{\nu_n}{\lambda_m}\right)^{0.5} [1 + (-1)^m] + 2L(\nu_n)^{0.5}(p_0 + p_e) \times$$
$$\times \sum_{k=1}^{\infty} \left\{\frac{b_k}{\alpha}\left[\sin\frac{\alpha}{2}\cos\left(\gamma t - \frac{\alpha}{2}\right)\right] - \frac{b_k}{\beta}\left[\sin\frac{\beta}{2}\cos\left(\gamma t - \frac{\beta}{2}\right)\right]\right\} -$$
$$- p_e L(\nu_n)^{0.5} \sum_{k=1}^{\infty} b_k \left[\frac{\cos\gamma t}{\alpha^2}(\cos\alpha + \alpha\sin\alpha - 1) + \frac{\sin\gamma t}{\alpha^2}(\sin\alpha - \alpha\cos\alpha) -\right.$$
$$\left. - \frac{\cos\gamma t}{\beta^2}(\cos\beta + \beta\sin\beta - 1) - \frac{\sin\gamma t}{\beta^2}(\sin\beta - \beta\cos\beta)\right], \tag{15}$$

where $\alpha = (k\omega_0 - (\lambda_m)^{0.5})L$; $\beta = (k\omega_0 + (\lambda_m)^{0.5})L$; $\gamma = k\omega_0 v$; we solve (10) and get after certain steps that

$$P_{nm}(t) \simeq \frac{p_0^2}{(\nu_n\lambda_m)^{0.5}} \exp(-Nt) + \left\{\left(\frac{\lambda_m}{\nu_n}\right)^{0.5} \frac{[(p_0 + p_e)^2 + (-1)^{m+1} p_0^2]}{\nu_n + \lambda_m} +\right.$$
$$+ \left(\frac{\nu_n}{\lambda_m}\right)^{0.5} \left[p_0^2 + p_e^2 + (-1)^m p_e^2 + \frac{2p_e^2(-1)^m}{\lambda_m L^2} - \frac{2p_e^2}{\lambda_m L^2} + \alpha p_e p_0 +\right.$$
$$\left.\left. + 2p_e p_0(-1)^m\right]\right\} \left[1 - \exp(-Nt) + \frac{2(\nu_n)^{0.5}}{M} L(p_0 + p_e) \times\right.$$

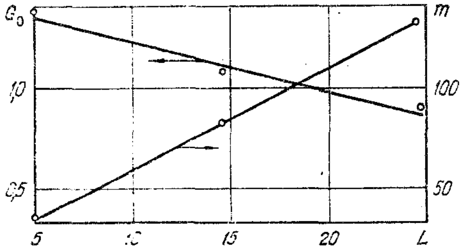

Fig. 4. Optimum throughput G_0, kg/sec, and calculated values of m for horizontal pipelines of various length L, m; $D = 2.1 \cdot 10^{-2}$ m, material alumina.

$$\times \sum_{k=1}^{\infty} b_k \left\{ \frac{\sin\frac{\alpha}{2}}{\alpha} \left[\frac{\Theta - T\exp(-Nt)}{\gamma^2 + N^2} \right] - \frac{\sin\frac{\beta}{2}}{\beta} \times \left[\frac{S - R\exp(-Nt)}{\gamma^2 + N^2} \right] \right\} - \frac{p_e L (\nu_n)^{0.5}}{M} \sum_{k=1}^{\infty} b_k \left\{ \left[\frac{V - N\exp(-Nt)}{\gamma^2 + N^2} \times \left(\frac{\cos\alpha + \alpha\sin\alpha - 1}{\alpha^2} - \frac{\cos\beta + \beta\sin\beta - 1}{\beta^2} \right) + \left[\frac{W - \gamma\exp(-Nt)}{\gamma^2 + N^2} \right] \times \left(\frac{\sin\alpha - \alpha\cos\alpha}{\alpha^2} - \frac{\sin\beta - \beta\cos\beta}{\beta^2} \right) \right] \right\}, \quad (16)$$

where the symbols are

$$N = \frac{1}{M}(\nu_n + \lambda_m); \quad T = N\cos\frac{\alpha}{2} + \gamma\sin\frac{\alpha}{2};$$

$$\Theta = N\cos\left(\frac{\alpha}{2} + \gamma t\right) + \gamma\sin\left(\frac{\alpha}{2} + \gamma t\right);$$

$$S = N\cos\left(\frac{\beta}{2} - \gamma t\right) - \gamma\sin\left(\frac{\beta}{2} - \gamma t\right); \quad R = N\cos\frac{\beta}{2} - \gamma\sin\frac{\beta}{2};$$

$$V = N\cos\gamma t + \gamma\sin\gamma t; \quad W = N\sin\gamma t - \gamma\cos\gamma t.$$

The components of the volume infiltration force are as follows:

$$\frac{\partial}{\partial x} p^{0.5} \simeq \frac{\sum_{n=0}^{\infty}\left[\sum_{m=1}^{\infty} P_{nm}(t)\,\lambda_m^{0.5}\cos\lambda_m^{0.5} x\right]\sin\nu_n^{0.5} z}{\left\{HL\sum_{n=0}^{\infty}\left[\sum_{m=1}^{\infty} P_{nm}(t)\sin\lambda_m^{0.5} x\right]\sin\nu_n^{0.5} z\right\}^{0.5}}, \quad (17)$$

$$\frac{\partial}{\partial z} p^{0.5} \simeq \frac{\sum_{n=0}^{\infty}\left[\sum_{m=1}^{\infty} P_{nm}(t)\sin\lambda_m^{0.5} x\right]\nu_n^{0.5}\cos\nu_n^{0.5} z}{\left\{HL\sum_{n=0}^{\infty}\left[\sum_{m=1}^{\infty} P_{nm}(t)\sin\lambda_m^{0.5} x\right]\sin\nu_n^{0.5} z\right\}^{0.5}}. \quad (18)$$

We see from (15)-(18) that the air pressure and bulk infiltration force take the form of undamped oscillations for $t \to \infty$, with the frequency dependent on the speed of propagation of the perturbation at the surface of the bed.

It is clear that provided

$$\alpha = 0, \quad \text{i.e.,} \quad \frac{\pi m}{L} = k\omega_0, \quad (19)$$

the pressure oscillations in the bed will be in phase with the surface perturbation, then the bulk infiltration force is maximal, which therefore increases the carrying capacity of the air flow.

Figure 4 shows the maximal throughput of a horizontal pneumatic transport pipeline for various lengths, together with the calculated values of m for each of the optimal states. The m = f(L) relationship allows one to determine ω_0 and hence the air speed v giving optimum performance.

NOTATION

$p = P^{0.5}$ is the pressure, Nm^{-2};
p_e, p_0 are the initial and atmospheric pressures, Nm^{-2};
μ is the concentration, kg/kg;
m_0 is the porosity;
v_0, v are the initial air speed and speed relative to material, m/sec;
L is the pipeline length;
H is the depth of bed in tube;
x, z are the coordinates;
t is the time.

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REMOVAL OF A LIQUID FROM AN OPEN-CELL BODY BY FLUIDIZED POROUS PARTICLES 1.

E. N. Prozorov, V. M. Starov, and N. V. Churaev

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It is shown that an analytic description can be given for the elimination of a bound material from a porous body immersed in a fluidized bed composed of small porous particles; the equations for fluid transport in a porous space can be used.

Here we consider the elimination of a bound fluid from a porous ceramic semifinished product during preliminary thermal processing in a fluidized bed [1-3].

Pure-oxide ceramics are produced mainly in semifinished form by hot pressing with a wax binding agent [4]. A major step in manufacturing such components that precedes the final firing is to eliminate the binding agent, which may be performed in a fluidized bed [5]. The process is operated at temperatures below the onset of evaporation of the binding agent. In that case, the vapor transport can be essentially neglected, so the internal mass transfer in the porous system occurs only in the liquid state.

A difference of our treatment from previous ones [6, 7] is that we derive solutions from the liquid-transport equations for film motion [8, 9] in a model porous medium. The model is a system consisting of capillaries of radii R_1 and R_2 interconnected throughout their length. This corresponds to the actual porous structure of numerous ceramic materials, in particular in that it fits the bimodal pore-size distribution [10, 11]. If the body is immersed in a fluidized bed at a temperature well below the evaporation point of the liquid, the only cause of external mass transport is liquid loss to the particles on collision with the surface (Fig. 1).

The capillary potential of a porous particle $P_p = 2\sigma \cos\theta/r$ is less than the potential of the liquid at the surface of the body $P_0(\tau)$, so the liquid is drawn into the capillaries of the particles when the latter are near the surface.

The following is the equation for the momentum change for the liquid in a particle capillary:

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