RESULTS OF A STUDY CONCERNING THE PERFORMANCE OF AIR EJECTORS FOR TRANSPORTING DISPERSE MATERIALS

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UDC 621.694.2:541.182.3

Results of comparative tests are shown which describe the performance characteristics of various ejector designs, and equations are derived which relate the parameters of a two-phase stream flowing through an air ejector.

Some applications justify the use of air injectors for transporting disperse material (aeration of granaries, or mechanization of secondary operations in crowded storage facilities, etc.). The decisive factors in these cases are the advantages of ejectors (simplicity of design and operation, small size and weight, reliability of performance). Three types of ejectors (Fig. 1) were tested for a comparative performance evaluation: ejector A with an axially installed nozzle and with transverse air suction, ejector B with a tangentially installed nozzle (a vortex tube), and the straight-flow ejector C with both the nozzle and the suction tube installed axially. Ejector A is at present used most widely for transporting gases and liquids. Such an ejector was tested for transporting also two-phase (air–grain) systems, but the results have shown that clogging in the mixing chamber can cause a shutdown. Better results were obtained with ejector C. Even with its inlet spout in the path of the throughfeed, its output capacity was, under the same conditions, still the highest of all. The vortex tube B produced the least rarefaction and its output capacity was lowest. The rarefaction ΔP produced in the receiving chamber of ejectors is shown in Fig. 2 as a function of the air ejection factor, at a constant prenozzle pressure. Curves 1 and 1a have been plotted for $P_0 = 5 \cdot 10^5$ and $3.2 \cdot 10^5$ P in a straight-flow ejector. Curves 2 and 2a have been plotted for the same pressures in ejector A. According to Fig. 2, the characteristic of a straight-flow ejector passes through a minimum. The characteristic of ejector A is drooping, with the ejection factor approximately half as large

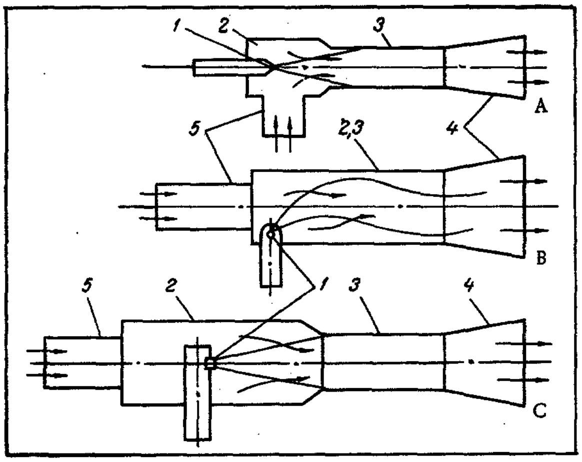

Fig. 1. Schematic diagram of air ejectors: 1) nozzle; 2) mixing chamber; 3) stabilizer; 4) diffuser; 5) suction duct.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 23, No. 4, pp. 650-654, October, 1972. Original article submitted February 8, 1972.

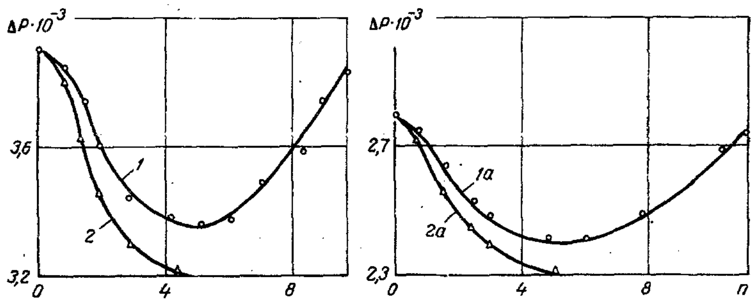

Fig. 2. Characteristics of air ejectors: $\Delta P = f(n)$.

as for ejector C. Our tests have shown that preventing critical operation and possible shutdown of an ejector requires that the velocity in the suction duct be at least 15% higher than the forced-fall velocity of solid particles.

The design of an air ejector is based on the equation of momentum conservation in a two-phase (monodisperse solid particles in air) stream:

$$1.82\,\varphi_{\text{п}} f P_0 \left[1-\left(\frac{P}{P_0}\right)^{\frac{k-1}{k}}\right]^{0.5} + \int\limits_{f_2} \rho_2 u_2^2 (1+\mu_s\varphi_s)\,df = \int\limits_{f_3} \rho_3 u_3^2 \left(1+\mu_s\varphi_s \frac{n}{1+n}\right) df + \Delta I. \tag{1}$$

The equation of mass conservation, with the velocity distributed nonuniformly across the section, can be written as

$$0.686\,\varphi_{\text{п}} f_1 (P_0\rho_0)^{0.5} + \int\limits_{f_2} \rho_2 (1+\mu_s)\, u_2\, df = \int\limits_{f_3} \rho_0 u_3 \left(1+\mu_s \frac{n}{1+n}\right) df. \tag{2}$$

The equation of mechanical energy balance during mixing and transporting a two-phase stream will be written in dimensionless form:

$$1 + \frac{n\mu_s\varphi_s^2 u_2^2}{u_1^2+nu_2^2} = \frac{(1+n)\,u_3^2}{u_1^2+nu_2^2} + \frac{n\mu_s\varphi_s^2 u_3^2}{u_1^2+nu_2^2} + \frac{2n\mu_s(h_2-h_1)}{u_1^2+nu_2^2} + \Delta\omega, \tag{3}$$

and the relative loss of mechanical energy $\Delta\omega$ will then be related to the energy dissipation in the mixing process, according to (3), as follows:

$$\Delta\omega = 1 - \frac{n\mu_s\varphi_s(u_3^2-u_2^2) + (1+n)\,u_3^2 + 2n\mu_{\text{т}}(h_2-h_1)}{u_1^2+nu_2^2}, \tag{4}$$

and in the case of zero concentration

$$\Delta\omega = 1 - \frac{(1+n)\,u_3^2}{u_1^2+nu_2^2}. \tag{5}$$

On the basis of the continuity equation, we can express the main transverse ejector dimension as

$$\frac{f_2}{f_1} = \left(\frac{2}{k+1}\right)^{\frac{1}{k-1}} (1+n)\,\frac{a_3}{u_3}\cdot\frac{P_0}{P_3}\left(\frac{T_{03}}{T_{01}}\right)^{0.5} \tag{6}$$

The relation between individual parameters of a two-phase stream and the geometrical dimensions of an ejector can be established by solving Eqs. (1), (2), (4), and (6). Most difficult in solving this problem is estimating the relative loss of momentum $\Delta I/(I_1 + I_2)$. Since it is impossible to calculate this loss theoretically, hence the problem must be solved experimentally. A universal curve of $\Delta I/(U_1 + I_2) = f(n)$ is shown in Fig. 3 for an ejector where pure air is sucked in under various operating conditions, according to which the loss of momentum decreases with a higher ejection factor. An explanation for this is that, as the velocity of the suction stream increases, the loss of momentum due to impact between this stream and the working stream decreases.

Another difficulty in solving these equations is accounting for the uniform velocity distribution across the tube section. Our tests and generalization of our as well as of other authors' results have yielded the following approximate equation for the velocity distribution inside smooth cylindrical tubes carrying a turbulent stream within the range of Mach number Ma < 0.6:

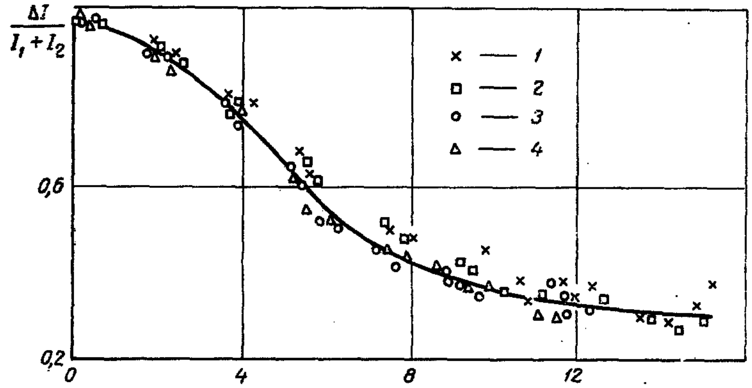

Fig. 3. Relative loss of momentum of an air stream in the ejector, as a function of the ejection factor: 1) $P_0 = 2.2 \cdot 10^5$ P; 2) $3.4 \cdot 10^5$ P; 3) $5.0 \cdot 10^5$ P; 4) $5.6 \cdot 10^5$ P.

$$\varphi_u = \frac{u}{u_0} = 1 - \left\{-\frac{1}{c}\ln\left[1-(1-e^{-c})(1-Y)\right]\right\}^m, \tag{7}$$

where c and m denote empirical constants. At Re = $4 \cdot 10^3$–$3.2 \cdot 10^6$ we found c = 7.2–11.2 and m = 1.02.

After inserting (7) under the integral in Eqs. (1) and (2), it is possible, by methods of approximate integration, to estimate the mass flow rate as well as the momentum and the kinetic energy at a given section. The mean-integral (with respect to mass, momentum, or kinetic energy) velocities can be calculated by the following universal relations:

$$\bar{u}_G = (0.700 + 0.0262 \lg \mathrm{Re})\, u_0, \tag{8}$$

$$\bar{u}_I = (0.740 + 0.0214 \lg \mathrm{Re})\, u_0, \tag{9}$$

$$\bar{u}_E = (0.769 + 0.0187 \lg \mathrm{Re})\, u_0. \tag{10}$$

Using relations (8)-(10) does appreciably simplify the subsequent calculations. Thus, for example, the mass flow rate becomes

$$G = \rho f \bar{u}_G, \tag{11}$$

the momentum becomes

$$I = \left(\frac{0.740 + 0.0214 \lg \mathrm{Re}}{0.700 + 0.0262 \lg \mathrm{Re}}\right)^2 \rho f \bar{u}_G^2, \tag{12}$$

and the kinetic energy becomes

$$E = \left(\frac{0.769 + 0.0187 \lg \mathrm{Re}}{0.700 + 0.0262 \lg \mathrm{Re}}\right)^3 \rho f \bar{u}_G^3 \tag{13}$$

at a given section.

With the aid of relations (11)-(13), one can determine the geometrical dimensions of the through-feed segment for an ejector at a given concentration of disperse material in the stream. The choice of the maximum concentration depends on the limiting minimum velocity along the suction duct to ensure a reliable transport of the disperse material. An excessively high concentration could reduce the air velocity down to the fall velocity of particles and this could result in clogging up the system.

Energy losses on transporting a two-phase stream depend on many factors such as: the density of the carrier, the density and the concentration of the solid phase, the stream velocity, the size and the shape of particles, etc. The quantity of energy necessary for transporting a unit mass of disperse material (energy consumption of an air ejector) can be expressed as:

$$\frac{L}{G_s} = \frac{RT_{01}}{(k-1)\,n_s\mu}\left[1 - \left(\frac{P}{P_0}\right)^{\frac{k-1}{k}}\right]. \tag{14}$$

A measurement of an air ejector performance in transporting wheat grain has shown a range varying from 6 to 10 m at a pressure $P_0 = 5 \cdot 10^5$ P, with the ejector axis inclined at an angle of about 40°, and decreasing with a higher concentration, i.e., with a higher output capacity. The maximum ejection factor for a grain was $n_T = 15$, with a suction duct 2 m long and with a specific energy consumption of 5.4 kJ/kg. The drag coefficient for single grains depends on their concentration in the stream: at $k_c = 0.01$–$4.0\ kg/m^3$ the drag coefficient remains almost constant and equal to $\xi_T = 0.472$, at $k_c = 4$–$8\ kg/m^3$ it is equal to $\xi_T = 0.472$–0.400, and at $k_c > 9\ kg/m^3$ it is equal to $\xi_T = 0.390$.

In the case of nonisothermal two-phase streams there occurs a heat transfer between a grain and the carrying air. According to our test results, we obtain the following empirical relation:

$$Nu_s = 0.785\, Re_s^{0.56} \exp(-0.01\, k_c). \tag{15}$$

With these formulas and relations based on test results, it is possible to design an air ejector for given range and output capacity, and also to select the appropriate compressed-air characteristics.

NOTATION

- ρ is the density;
- u_0 is the velocity along the tube axis;
- f is the section area;
- k is the adiabatic exponent;
- μ is the molecular weight of air;
- P is the gas pressure;
- ΔP is the rarefaction in the receiving chamber of an air ejector;
- φ_n is the nozzle flow coefficient;
- φ_s is the slip;
- n is the ejection factor;
- μ_s is the weight concentration of solid phase in the stream;
- α is the velocity of sound;
- ΔI is the loss of momentum;
- $\Delta\omega$ is the relative loss of energy;
- T_0 is the stagnation temperature;
- φ_u is the velocity coefficient;
- $Y = y/r_0$ is the relative distance from the tube wall;
- $\bar{u}_G$ is the mean-integral velocity, with respect to mass;
- $\bar{u}_I$ is the mean-integral velocity, with respect to momentum;
- $\bar{u}_E$ is the mean-integral velocity, with respect to energy;
- k_c is the volume concentration;
- Re is the Reynolds number;
- Nu is the Nusselt number.

Subscripts

- 1 denotes the working stream of air;
- 2 denotes the suction stream of air;
- 3 denotes the mixed stream of air;
- s denotes the solid phase;
- 0 denotes the air before entering the nozzle.

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