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A METHOD OF DETERMINING THE PERFORMANCE OF LOW-DENSITY GASDYNAMIC TUBES

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The parameter describing the efficiency of a gas-pumping system is the rate or pumping speed. In contemporary vacuum pumps this parameter can have quite high values, e.g., vapor-jet pumps having pumping speed ~15,000 liter/sec and higher at pressures of 10^{-3}-10^{-4} torr [1, 2], while cryogenic pumps have values of 10^6-10^8 liter/sec at the same pressures [3-5]. With these parameters the gas-flow rate per second under steady conditions can be as high as tens of grams. To determine the performance of gas-pumping systems one usually must measure a considerable number of parameters. Here we propose a method of determining the performance from the geometrical dimensions of the jet flow, based on the fact that the gas-flow rates through the nozzle and through the pumping system are equal. The gas-flow rate through a nozzle can be written in the form

$$G_c = \mu A(k) F_* p_0/(RT_0)^{0.5}, \tag{1}$$

where μ is the mass-flow coefficient (in many cases we can assume this to be 1 for simplicity); $A(k) = [2/(k+1)]^{1/(k-1)}[2gk/(k+1)]^{0.5}$ is the discharge coefficient; $k = c_p/c_V$ is the specific-heat ratio; F_* is the nozzle throat area; p_0 and T_0 are the stagnation pressure and temperature, respectively; and R is the gas constant.

The gas flow rate through a pumping system can be expressed in the form

$$C_{\text{pump}} = S\gamma p_\infty/p_\gamma, \tag{2}$$

where S is the efficiency; γ is the specific weight; p_∞ is the pressure in the working volume, created by the pumping system; and p_γ is the pressure at which the specific weight is determined.

Then, from equality of Eqs. (1) and (2), we obtain the expression

$$S = \frac{A(k)\,\pi r_*^2 p_0 p_\gamma}{(RT_0)^{0.5}\,\gamma p_\infty}, \tag{3}$$

which is a starting point for determining the performance of the pumping system. It is known [6-8] that the geometric dimensions both longitudinal and transverse, of jets discharging into a rarefied volume, depend on the degree of expansion of the gas flow p_0/p_∞. The quantity that can be most conveniently measured is the distance along the jet axis from the nozzle throat to the point of minimum total pressure, corresponding to the position of the Mach disk. The measurement is carried out by a very simple total pressure sensor, for which the measurement technique is well developed. It is also possible to determine the position of the Mach disk by some other method (e.g., by visualizing "cold" jet flows by the "glow discharge" or the electron-beam method, and also to record parameters such as the density or the static pressure).

For a wide range of expansion of the gas flow (Fig. 1, solid line), the distance from the Mach disk x_m at Knudsen $Kn_{0,d*}(p_0/p_\infty)^{0.5} < 2 \cdot 10^{-3}$ is $x_m = 1.35\,(p_0/p_\infty)^{0.5}\, r_*$.

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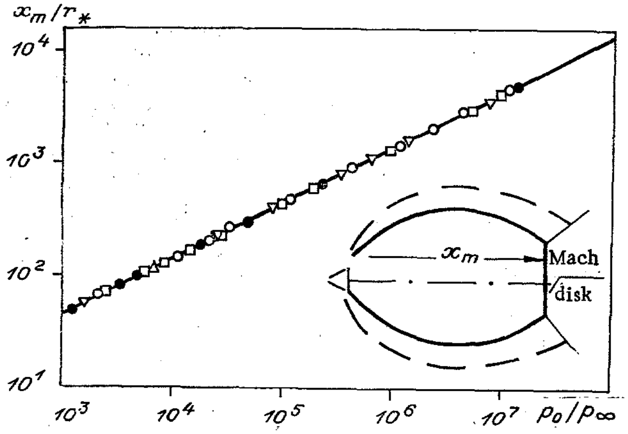

Fig. 1

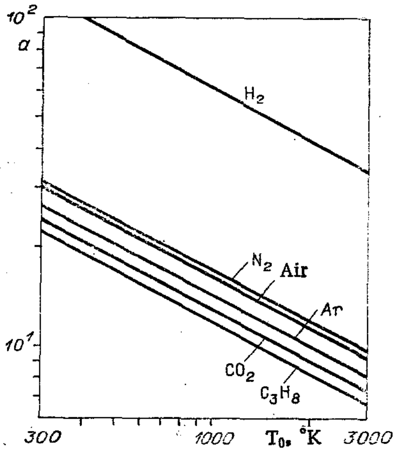

Fig. 2

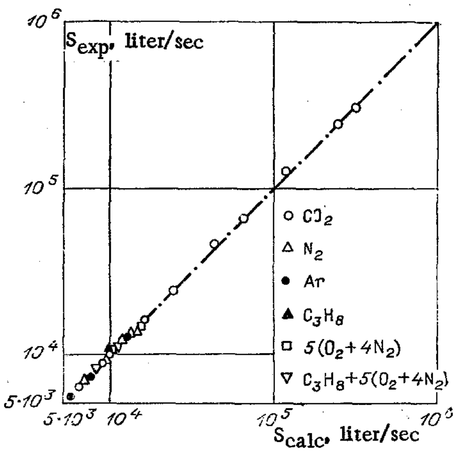

Fig. 3

Then Eq. (3) can be reduced to the very simple form

$$S = ax_m^2, \tag{4}$$

where $a = 1.72A(k)p_\gamma/(RT_0)^{0.5}\gamma$.

The values of the coefficients $a = f(T_0)$ are shown in Fig. 2 for various gases.

In order to give the efficiency S in Eq. (4) in the dimensions liter/sec, the distance to the Mach disk x_m must be measured in centimeters. By using the graph obtained and Eq. (4) we can easily determine the performance of the pumping system of a mass-flow facility with an accuracy sufficient for engineering purposes.

The results of the calculations have been verified experimentally in a low-density gasdynamic tube having a vacuum chamber of volume ~3 m³ and a rather high-power pumping system. It consisted of two type VN-6G fore-vacuum mechanical pumps, a type BN-15,000 vapor-jet booster pump, and three cryogenic panels of total area ~30 m², located in the vacuum chamber. The cryopanels were cooled to a temperature of 77°K using liquid nitrogen.

The working substance was discharged into the vacuum chamber from a heated reservoir (electrothermal or ohmic heater) through sonic and supersonic nozzles of different sizes. The working substances used were the gases nitrogen, argon, carbon dioxide, and propane, and also a mixture of gases formed by burning propane in air. The stagnation pressure was varied from 100 torr to 3.5 kg/cm² at stagnation temperatures from 300 to 1500°K. For the typical parameters quoted the degree of gas-stream expansion $p_0/p_\infty = 1\cdot10^4$–$2.5\cdot10^7$, and the mass-flow rate was 0.15–5.0 g/sec. The flow rate through the nozzle was measured using types RS-3 and RS-5 rotameters, calibrated with a type GSB-400 gas counter. The gas-flow rate into the vacuum chamber was 0.05 g/sec, due to imperfect sealing. Figure 3 shows a comparison of the performance of the low-density gasdynamic tube with calculation under various conditions. Most of the results were obtained with pumping rates below 15,000 liter/sec, when the above-mentioned gases, except for CO_2 and C_3H_8, did not freeze out on the cryosurfaces at liquid-nitrogen temperature, but were pumped using the vapor-jet and mechanical pumps. The performance of the facility above 15,000 liter/sec was verified using CO_2 and C_3H_8. Figure 3 shows good agreement between the calculated and experimental values of performance although the new method is only an estimate and does not claim high accuracy.

The error of the method is determined by the characteristics of the measuring systems used to determine the position of the closing shock of the jet flow and also by a number of features of jet flows obtained in this kind of facility. These features include possible condensation of the working substances, which leads to the closing shock being displaced toward the nozzle exit (in the present investigation condensation was eliminated by heating the working substances), and rarefaction, which causes the closing shock to undergo transition from a Mach configuration to an X shape and therefore to an increase in the results obtained for $Kn_{0,d_*} \cdot (p_0/p_\infty)^{0.5} < 2 \cdot 10^{-3}$.

The method has limitations determined by the size of the working volume of the gasdynamic facility, on the one hand, and on the other hand, by additions corresponding to flow transition from continuum to free-molecular, when the wave structure of the jet flow becomes smeared.

It should be noted that the method described can be especially useful in determining the performance of cryopumps and cryotraps, but has an upper limit in its application, due to interaction of the jet flow with the vacuum-chamber surfaces.

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