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EXPERIMENTAL STUDY OF GAS FLOW OUT OF A POROUS PLATE INTO VACUUM

L. L. VASILIEV, YU. A. LAPSHIN and A. N. PISKUNOV
Heat and Mass Transfer Institute, Byelorussian Academy of Sciences, Minsk, U.S.S.R.

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Abstract—An experimental study is carried out of gas flow out of a porous plate into vacuum with ratio $N = P_0/P_\infty$ of stagnation pressure P_0 in the prechamber to that at infinity P_∞ varying within $2{\cdot}3 \times 10^3 < N < 4{\cdot}85 \times 10^4$. Permeability of the test porous plates was over the range $5\,\text{Darcy} \leqslant K \leqslant 30\,\text{Darcy}$; the porosity ranged within $0{\cdot}253 \leqslant \Pi \leqslant 0{\cdot}78$. Flow structures, pressure distributions in jets, variation of stagnation pressure P_{0s} on the exit section of a porous plate were studied. Introduction of new parameters $\zeta = P_{0s}/P_0$ and $N_s = P_{0s}/P_\infty$ determining the flow pattern behind the porous plate was substantiated. The measuring technique for Mach numbers in jets behind a porous plate was considered.

NOMENCLATURE

M,	Mach number;
P,	static pressure;
P_0,	stagnation pressure in prechamber;
P_0',	stagnation pressure behind the shock wave;
P_{0s},	total pressure head on the plate exit section;
P_∞,	pressure in the chamber outside the jet;
g,	specific weight;
γ,	$= C_p/C_v$, specific heat ratio;
K,	permeability;
Π,	porosity;
d,	filling fraction diameter;
D,	porous plate diameter;
δ,	porous plate thickness;
ζ,	$= P_{0s}/P_0$, recovery coefficient of the total pressure head;
N,	$= P_0/P_\infty$, pressure-drop coefficient;
N_s,	$= P_{0s}/P_\infty$, pressure ratio on plate exit section;
L_M,	distance from plate exit section to the Mach disk;
D_M,	Mach disk diameter;
m, n,	numerical coefficients determined from experimental data;
Re,	Reynolds number based on the Pitot tube diameter.

FOR A long time a jet out of a porous plate was considered to achieve uniform subsonic conditions after disordered flow from micronozzles in metal ceramics. Few works are available on supersonic jets out of porous plates. Supersonic velocities are found in one of the earlier works [1] on outflows from porous plates at high pressure ratios P_0/P_∞. Large zones of supersonic flows in the downflow behind porous materials had not been earlier found and the possibility of such zones was ignored. A jet with the maximum Mach number ($M = 3{\cdot}5$) was obtained in later work [2]. A flow behind the plate was found to be sufficiently homogeneous and to have a small gradient that allows its usage in aerodynamic experiments on external flow. Such a way of flow production may successfully compete with supersonic nozzles in low-density gasodynamic installations.

The possibility of obtaining supersonic jets with high Mach numbers behind the porous plates is demonstrated in [3, 4].

The available few experimental data are incomplete and give a vague idea of flows behind a porous plate at large pressure drops. The structure of the resultant jets, the character of shock wave arrangement, isentropic core sizes and pressure distribution are not also studied enough. The effect of porous body characteristics on flow parameters is not considered in all enumerated works and the physics of gas expansion into vacuum from a porous plate surface is not sufficiently studied. It should be pointed out that the presence of such supersonic flows behind porous plates is of great importance for formulation of the heat-protection problem at high-rate injection. Therefore the necessity of further investigations in this field is quite clear.

The present study was carried out on a low-density wind tunnel with the maximum rate of gas pumping of 57 000 l/s over the pressure range of 10^{-2}–10^{-3} torr. The installation (Fig. 1) is fitted with three-position remote-indicating traversing equipment, the displace-

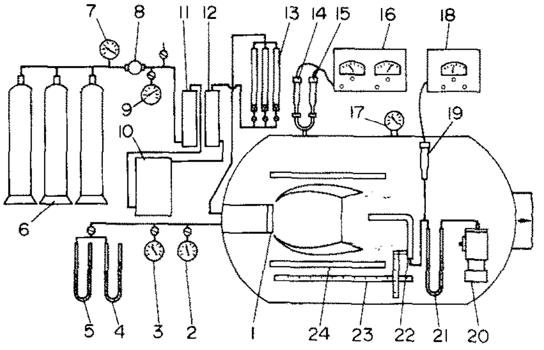

FIG. 1. Schematic diagram of measuring equipment 1, porous plate; 2, standard vacuum gauge; 3, standard manometer; 4, 5, oil and mercury U-shaped manometer; 6, gas vessels; 7, high pressure manometer; 8, reductor; 9, manometer; 10, gas dehumidifier; 11, 12, gas filters; 13, rotameters; 14, thermocouple valve; 15, ionization valve; 16, vacuum gauge BIT-2; 17, standard vacuum gauge; 18, vacuum gauge BT-2A; 19, thermocouple valve; 20, vacuum pump; 21, U-shaped manometer; 22, Pitot tube; 23, traversing device; 24, visulialization plates.

ments of which were recorded within 0·01 mm by a cathetometer KM–8. The general gas flow was visualized following the glow discharge technique. A high-voltage transformer served as a power source. The output voltage was smoothly regulated from 0 up to 10 000 V by variation of the input voltage of the transformer from 0 up to 220 V. The voltage sufficient for a glow discharge to be produced may thus be chosen depending on rarefaction degree and gas flow rate through the nozzle. One potential of controllable high voltage of the secondary winding is supplied to the chamber casing, the second one, to two parallel aluminium plates placed symmetrically about the flow axis. The plate surfaces facing the chamber walls are electrically insulated. A uniform electrical field is generated between the plates due to the high-voltage potential. Stable uniform luminescence of a glow discharge is formed between the plates, contrary to the case of different potentials on the plates. At a pressure of about 10^{-3} torr, 5000–6000 V is sufficient for a glow discharge; at higher voltages (the distance is 300 mm) undesirable ruptures of the chamber walls may arise and luminescence may become unstable and non-uniform. Air (a working gas) was supplied to the prechamber through a flow system consisting of filters 10, 11 and a dryer 12. Gas was heated by an ohmic pipe heater. The gas flow rate in the flow system was controlled by PC–3-type rotometers 13. The pressure of the stagnant flow was measured from the pressure in the prechamber by the following apparatuses used for different pressure ranges: (a) by standard manometer 3, 0·6-class, with the measuring range 0–4 kg/cm^2; (b) by U-shaped manometers 5, 4 filled with dibutyl phthalate with the specific weight $g = 1{\cdot}041$ g/cm^3 at 20°C or with mercury; (c) by standard vacuum gauge 2.

The total pressure behind the shock wave was measured by a Pitot tube with plane face 22. A U-shaped standard manometer filled with dibutyl phthalate 21 was used for pressure measurements within the range 0·1–5 torr. The U-shaped manometer fitted in the chamber was provided with independent vacuum pumping to eliminate the pressure effect in it. AT–2-type thermocouple valve 19 and BT–2A-type vacuum gauge 18 were used over the pressure range 10^{-1}–10^{-2} torr. These were calibrated according to the MacLeod manometer before every run. The displacement of the meniscus of the liquid column from the initial position was measured by the cathetometer with accuracy of 0·01 mm. In the experiments use was made of a head 5 mm O.D. with the O.D.–I.D. ratio of 0·75. Measuring of the Mach number in a gas flow usually requires knowledge of the following parameters: the stagnant flow pressure P_0 (or the pressure in the prechamber), the total flow pressure behind the shock P_0'. With the ratio P_0'/P_0 known, the Mach number is determined from the Rayleigh formula for an isentropic flow [5]:

$$P_0'/P_0 = \left(\frac{2\gamma}{\gamma+1}M^2 - \frac{\gamma-1}{\gamma+1}\right)^{1/(1-\gamma)} \bigg/ \left[\frac{2}{(\gamma+1)M^2} + \frac{\gamma-1}{\gamma+1}\right]. \quad (1)$$

Substitution of P_{0s} for P_0 in the Rayleigh formula is made because the gas flow in the plate is non-isentropic.

To account for the flow non-isentropy effect, the Mach number was also determined from the ratio of the static pressure to that behind the shock wave [5]:

$$P/P_0' = \left(\frac{2\gamma}{\gamma+1}M^2 - \frac{\gamma-1}{\gamma+1}\right)^{1/(1-\gamma)} \bigg/ \left(\frac{\gamma+1}{2}M^2\right)^{\gamma/(\gamma-1)}. \quad (2)$$

The static pressure in the flow was measured by a conic gauge with an expansion angle of 10°. The correction for flow rarefaction was calculated by the parameter Re/M following the procedure described in work [6].

The pressure in the working chamber was measured by thermocouple 14 and ionization 15 valves and was controlled by a BIT–2-type vacuum gauge. For rough measurements of the rarefaction degree in a chamber a standard vacuum gauge 17 was used.

Samples produced by sintering under pressure of bronze powders with fraction diameters within $d = 0{\cdot}2 + 0{\cdot}315$ mm were used as porous test plates. The thickness of test plates was within 3 mm $< \delta <$ 10 mm, diameters of plates, within 30 mm $< D <$ 60 mm. Bronze porous plates with the permeabilities $5 < K < 20$ and porosities $20 < \Pi < 50$ were produced by a special technique. For producing plates with large permeabilities $K > 20$ and porosities $\Pi > 50$ use was made of multilayer samples obtained by pressing a great number of net layers of brass wire. Using this technique the plates, 30 mm $< D <$ 60 mm in dia and 3 mm $< \delta <$ 5 mm in thickness, were obtained. Permeability and porosity of the resultant plates were within 20 Darcy $< K <$ 30 Darcy, $0{\cdot}50 < \Pi < 0{\cdot}80$, respectively. Porous plates with the parameters $0{\cdot}253 < \Pi < 0{\cdot}78$ and 5 Darcy $< K <$ 30 Darcy were used in the experiments. The test plates were substituted for a nozzle at the prechamber outlet. The ratio of the pressure in the prechamber P_0 to the pressure at the infinity (for which the pressure in the vacuum chamber far enough from the flow zone was assumed) were controlled within $2{\cdot}3 \times 10^3 < N < 4{\cdot}85 \times 10^4$ by variation of the air flow rate in the prechamber and the pumping-out capacity during the experiments. The gas flows behind the plate were carefully investigated. The general flow pattern obtained by the glow discharge technique was photographed and then analysed. Besides, all the necessary quantities may be measured directly during the run with the help of special movable rules placed in the chamber. The stagnation pressure P_{0s} at the exit section of the plate was measured by a Pitot tube allowing the stagnation pressure to be measured directly at the plate exit section. Pressure distributions in flows behind the plates were carefully measured by the above methods and equipment.

As the experimental data have demonstrated, the flow behind the plate is a free under-expanded jet with barrel-shaped suspended shocks and the Mach disc (see Fig. 2). Besides, depending on permeability values K, as the pressure ratio N_s at the plate exit section increases

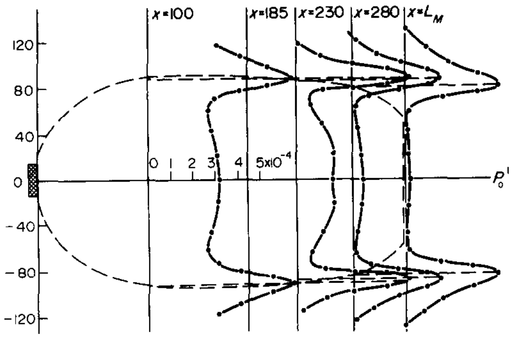

FIG. 2. Pattern of outflow from porous plate ($D = 30$ mm, $K = 5$ Darcy, $N = 2{\cdot}42 \times 10^4$).

and the jet density decreases, the barrel-shaped supersonic flow region becomes larger, the Mach disc (the central shock wave) is destroyed and transforms into an X-shaped shock wave with a subsequent supersonic flow. For example, in a flow out of a porous plate with permeability $K = 30$ Darcy the "Mach structure" becomes an X-shaped one with $N_s = 4{\cdot}4 \times 10^3$. For a plate with permeability $K = 5$ Darcy with $N_s > 6{\cdot}4 \times 10^3$ the flow structure was X-shaped. Measurements of stagnation pressure P_0' (Fig. 3) and the static pressure P distributions (Fig. 4) over the flow axis behind plates have revealed that the flow behind a plate may be divided into four zones. In the first zone 1 mm in width, adjacent to the instantaneous flow expansion occurs. This is followed by the second zone, about some centimeters in width with uniform radial parameter distributions and a small gradient of the flow parameters over the axis. The adiabatic expansion and increase of the flow rate up to the values close to the maximum flow rates into vacuum occur in the following zone. Near the Mach disc there is a large zone with the least longitudinal and radial gradients of these parameters and with the most uniform parameter distribution, respectively.

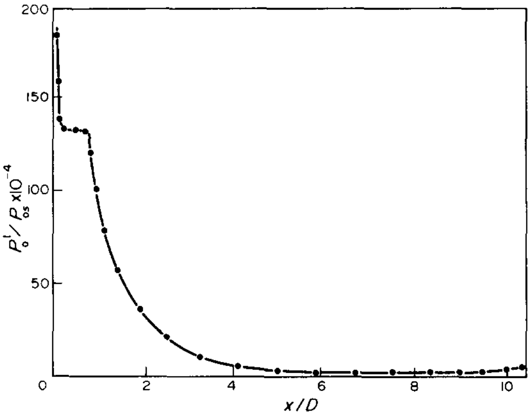

FIG. 3. Stagnation pressure distribution P_0' over the jet axis behind porous plate ($D = 30$ mm, $K = 5$ Darcy, $N = 2{\cdot}48 \times 10^4$).

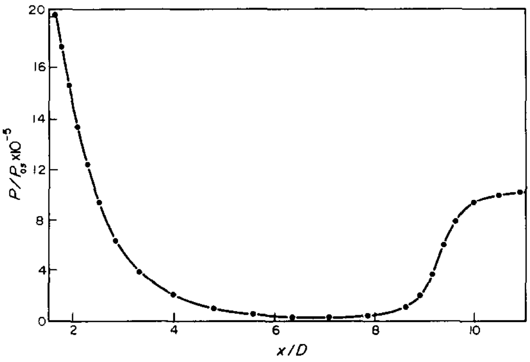

FIG. 4. Distribution of static pressure P over the jet axis behind the porous plate ($D = 30$ mm, $K = 5$ Darcy, $N = 2{\cdot}48 \times 10^4$).

The greatest experimental difficulty with gas flows behind a porous plate presents the fact that due to strong viscous dissipation in a flow through the plate the flow deceleration parameters are unknown because in this case gas parameters in the prechamber cannot be taken as the flow deceleration parameters. For estimation of irreversible losses in a gas flow through a plate we introduce the total pressure head recovery coefficient ζ defined by the formula

$$\zeta = P_{0s}/P_0 \tag{3}$$

where P_{0s} is the total pressure head on the exit section of the porous plate measured by the above technique.

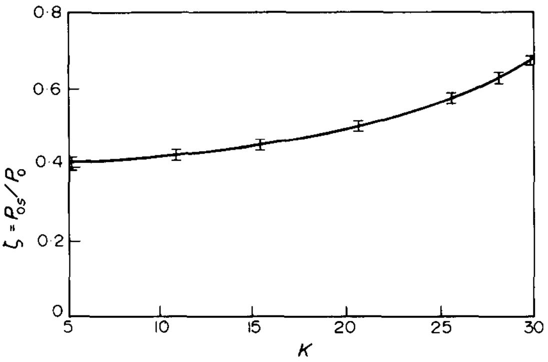

Fig. 5. Plot of total pressure recovery coefficient ζ vs permeability K of a porous plate.

Variation of this coefficient as permeability function of the test plates $\zeta = f(K)$ is shown in Fig. 5. According to these results viscous losses in the test plates decrease as the permeability increases. Variations of the pressure drop in this case slightly influences ζ.

Proceeding from the fact that viscous losses take place mainly in the gas flow inside a plate, we may conclude that properties of porous materials such as porosity Π, thickness δ, filling fraction size etc., and, in the end, permeability K influence only the irreversible losses inside the plate determined by coefficient ζ and the downflow behind the plate may be considered as a free gas flow from a source with a plane surface. Therefore, we may consider the external problem of a flow out of a porous plate surface as free gas expansion from a source with a plane transition surface with the diameter equal to the plate diameter into a medium with pressure of P_∞. The total pressure on the plate exit section P_{0s} should be taken as the stagnation pressure of this ideal source rather than the stagnation pressure in the prechamber P_0. The mathematical problem of a gas flow into vacuum was considered in Ladyzhensky's work [7]. Proceeding from the above said it may be concluded that the downflow development behind the plate is almost completely determined by introduced parameter $N_s = P_{0s}/P$. All these require the substitution of the stagnation pressure in the prechamber in the Rayleigh formula by the total pressure P_0 at the plate exit section and treatment of experimental data based on parameter $N_s = P_{0s}/P$ rather than on parameter $N = P_0/P$. Qualitative agreement of Mach numbers determined from formulas (1) and (2) verifies this method for a gas flow out of a porous plate into vacuum. This model describes most exactly the flow out of porous plates with a higher permeability ($20 < K < 30$ Darcy). For these plates Mach numbers calculated by formulas (1) and (2) coincide within the experimental accuracy. Incorrectness of the outflow model adopted may possibly be explained by the fact, that it neglects viscous losses outside the plate which in some cases may have real values. For slightly permeable plates the adopted model should probably include viscous dissipation in the mixing zone near the plate. Treatment of experimental data on the outflow geometry at the "Mach structure" on the basis of parameters ζ, N_s and D made it possible to describe approximately the flow structure in the form of power relations:

$$L_M/D = m_1 N_s^{n_1} \tag{4}$$

$$D_M/D = m_2 N_s^{n_2}. \tag{5}$$

Coefficients m and n were determined from plots of these relations in logarithm coordinates (Figs. 6 and 7).

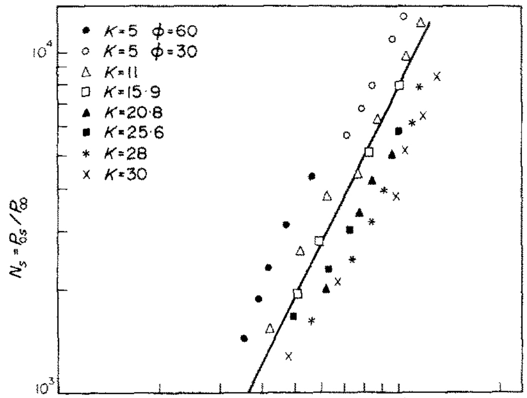

FIG. 6. Plot of a dimensionless distance to the Mach disc vs parameter N_s.

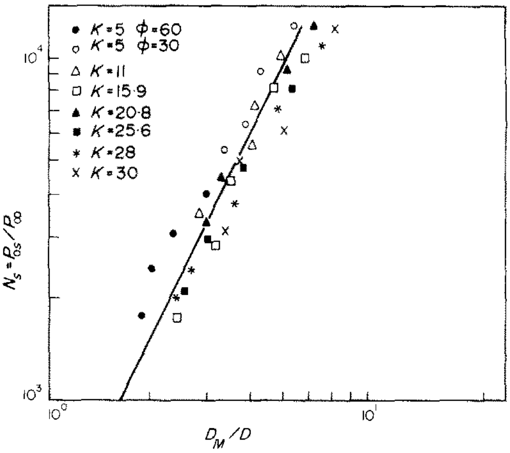

FIG. 7. Plot of dimensionless diameter of the Mach disc vs parameter N_s.

According to certain numerical values of these coefficients expressions (4) and (5) are of the form in the present case:

$$L_M/D = 0{\cdot}118\,N_s^{0{\cdot}5} \tag{6}$$

$$D_M/D = 0{\cdot}053\,N_s^{0{\cdot}5}. \tag{7}$$

With the account of $N_s = P_{0s}/P_0$, $N = P_0/P_\infty$ and $\zeta = P_{0s}/P_0$ expressions (6) and (7) may be transformed to

$$L_M/D = 0{\cdot}118\sqrt{(\zeta N)} \tag{8}$$

$$D_M/D = 0{\cdot}053\sqrt{(\zeta N)}. \tag{9}$$

Thus, with the empirical relation $\zeta = f(K)$ obtained (Fig. 5) and gas parameters in the prechamber and in the working chamber and the characteristics of the porous plates known, the flow geometry behind the plate may be determined.

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ETUDE EXPERIMENTALE DE L'ECOULEMENT D'UN GAZ A TRAVERS UNE PLAQUE POREUSE DANS LE VIDE

Résumé—Une étude expérimentale d'un écoulement de gaz à travers une plaque poreuse dans le vide est effectuée pour des rapports $N = P_0/P_\infty$ de la pression d'arrêt P_0 dans la chambre primaire à la pression à l'infini P_∞, qui varient entre $2{,}3.10^3 < N < 4{,}85.10^4$. La perméabilité de la plaque poreuse d'essai se situe dans le domaine 5 Darcy $\leqslant K \leqslant$ 30 Darcy et la porosité dans le domaine $0{,}253 \leqslant \pi \leqslant 0{,}78$. On a étudié la structure d'écoulement, les distributions de pression dans les jets et la variation de pression d'arrêt P_{0s} dans la section de sortie d'une plaque poreuse. L'introduction de nouveaux paramètres $\zeta = P_{0s}/P_0$ et $N_s = P_{0s}/P_\infty$ qui déterminent la structure de l'écoulement derrière la plaque poreuse a été justifiée. La technique de mesure des nombres de Mach dans les jets derrière une plaque poreuse a été considérée.

EXPERIMENTELLE UNTERSUCHUNG DER GASSTRÖMUNG AUS EINER PORÖSEN PLATTE IN EIN VAKUUM

Zusammenfassung—Eine experimentelle Untersuchung der Gasströmung aus einer porösen Platte in ein Vakuum wird durchgeführt, wobei des Verhältnis $N = P_0/P_\infty$ vom Staudruch P_0 in der Vorkammer zum Druck im Unendlichen P_∞ innerhalb $2{,}3 . 10^3 < N < 4{,}85 . 10^4$ variiert. Die Gasdurchlässigkeit der porösen Versuchsplatten lag im Bereich 5 Darcy $\leqslant K \leqslant$ 30 Darcy die Porosität lag im Bereich $0{,}253 \leqslant \pi \leqslant 0{,}78$. Strömungsstrukturen, Druckverteilungen in Düsen, unterschiedliche Staudrucke P_{0s} an der Austrittsseite einer porösen Platte wurden untersucht. Einführung neuer Parameter $\zeta = P_{0s}/P_0$ und $N_s = P_{0s}/P_\infty$, welche den Strömungszustand hinter der porösen Platte bestimmen, wurde begründet. Die Meßtechnik für Mach-Zahlen in Düsen hinter einer porösen Platte wurde betrachtet.

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ИСТЕЧЕНИЯ ГАЗА ИЗ ПОРИСТОЙ ПЛАСТИНЫ В ВАКУУМ

Аннотация — Проведено экспериментальное изучение истечения газа из пористой пластины в вакуум при изменении отношения давления торможения P_0 в форкамере к давлению на бесконечности равного $N = P_0/P_\infty$ в интервале $2{\cdot}3 \times 10^3 < N < 4{\cdot}85 \times 10^4$. Проницаемость исследуемых пористых пластин изменялась в пределах 5 Дарси $\leq K \leq$ 30 Дарси, пористость — $0{\cdot}253 \leq \Pi \leq 0{\cdot}78$. Изучалось структура течений, распределение давлений в струях, изменение торможения P_0 на срезе пористой пластины. В работе обосновано введение новых параметров $\zeta = P_{0s}/P_0$ и $N_s = P_{0s}/P_\infty$, определяющих характер течения за пористой пластиной. Рассматривается методика измерения чисел Маха в струях за пористой пластиной.