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UNSTEADY FLOW OF A GAS INTO VACUUM THROUGH A PERFORATED PLATE

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The problem of the unsteady flow of a gas into vacuum through a perforated plate is solved within the framework of an approach developed earlier [1]. Two steady orifice flow schemes are used to close the relations at the perforation. The corresponding results of calculations are given for each scheme. The present model, unlike the one proposed in [2, 3], preserves not only the mass flow of gas, but also its total enthalpy.

We direct the x axis along the normal to the perforated plate, which coincides with the plane $x = 0$. It is represented by the hatched strip in Fig. 1a. At time $t \leq 0$ the half-space $x < 0$ is filled with an ideal gas at rest. To the right of the plate is vacuum. At time $t = 0$ the gas begins to flow through the perforation. In terms of its formulation this problem is similar to the problem of the decay of an arbitrary discontinuity at a perforated plate and can be solved within the framework of the approach developed in [1].

If d is a typical linear dimension of the perforation and D is a typical wave propagation velocity, we can assume, as in [1], that for $t \gg d/D$ the flow through the perforation

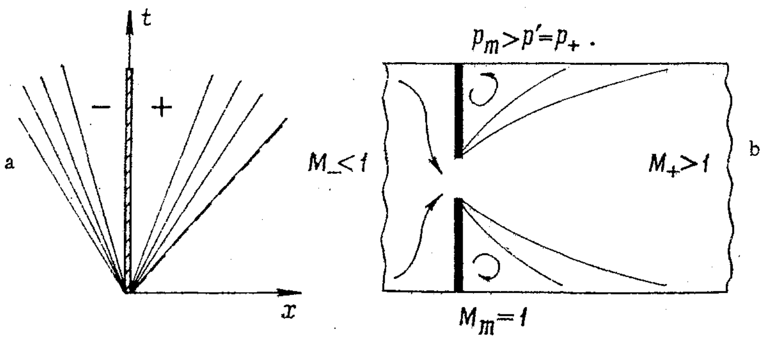

Fig. 1

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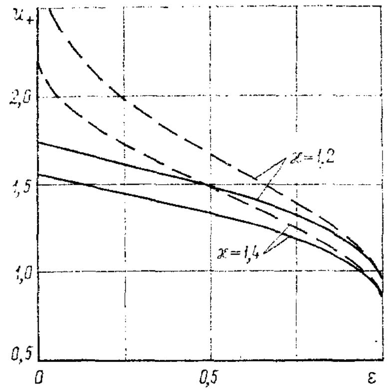

Fig. 2

is steady and for $|x| \gg d$ the flow is one-dimensional and self-similar (the flow pattern is shown in Fig. 1a). Centered rarefaction waves propagate in both directions from the plate. The wave traveling to the left through the rest gas accelerates it. As a result, the gas to the left of the plate acquires a velocity u such that critical flow takes place in the minimum cross section of the perforation. In blocked flow regimes the steady isentropic inflow scheme and the relations satisfied at the centered wave uniquely determine the intensity of the rarefaction wave and the flow parameters both in the minimum flow-through cross section of the perforation and immediately in front of the plate.

The outflow of gas into the domain $x > 0$ in the given situation is supersonic. A distinctive feature of the wave structure formed in the investigated problem, in contrast with the schemes considered for supersonic flow regimes in [1], is the presence of only one wave, propagating to the right. The contact discontinuity corresponding in this case to the front of the outflowing gas is represented by the dashed line in Fig. 1a and coincides with the outermost characteristic curve of the flow, which moves with the maximum velocity u_f.

Let $\varepsilon = S_m/S$ be the degree of constriction of the perforation, equal to the ratio of the minimum area S_m of the "flow-through" cross section to the total area S of the plate, let p be the pressure, ρ the density, i the specific enthalpy, and s the specific entropy. We attach the index m to the parameters in the minimum flow-through cross section, and the index + to the plate. We can then write the relations

$$(\rho u)_m \varepsilon = (\rho u)_+, \ (2i + u^2)_m = (2i + u^2)_+, \qquad (1)$$

which are universal and do not depend on the flow structure obtained in mixing and equalization of the flow after the perforation. The flow regime of interest to us in the given problem occurs with closed separation zones. Figure 1b shows the corresponding flow scheme through an element of the plate. As in [1], we obtain the deficient relation for the system (1) in two ways, first by adopting the hypothesis of isentropic supersonic expansion:

$$s_m = s_+ \qquad (2)$$

and, second, setting*

$$p' = p_+, \qquad (3)$$

where p' is the pressure acting on the right side of the plate.

As noted in [1], for $\varepsilon \geqslant 0.05$ the latter condition provides a better description of the experimental data on the sudden expansion of sonic flow. On the basis of (3) the condition of conservation of momentum in the x direction, written for the cross sections m and +, takes the form

$$p_+\varepsilon + \rho_+ u_+^2 = \varepsilon (p + \rho u^2)_m. \qquad (4)$$

Equations (1) and (4) augmented with the relations satisfied at the centered rarefaction wave can be used to determine the flow parameters to the right of the plate and the velocity of the outflowing gas front.

The results of using the foregoing model to calculate the flow of an ideal gas with

*In [1] the expression $p' = p_m$ in Eq. (1.10) should read: $p' = p_+$.

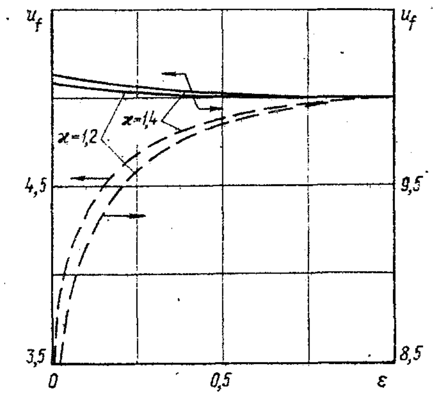

Fig. 3

adiabatic exponents $\varkappa$ = 1.4 and 1.2 through a perforated plate are shown in Figs. 2 and 3. All of the parameters shown are dimensionless; the velocity and density are referred to the sound velocity a_0 and density ρ_0 of the rest gas at t = 0, and the pressure to the quantity $\rho_0 a_0^2$.

Figure 2 shows the velocity of the gas to the right of the plate (in the domain +) as a function of the perforation ratio ε. The solid curves represent condition (3), and the dashed curves correspond to the isentropic flow hypothesis (2); for values of $\varkappa$ = 1.2 and 1.4, as $\varepsilon \to 0$ the latter curves arrive at the respective points $u_+ = 3.16$ and 2.24.

Figure 3 shows the velocity of propagation of the gas front for various values of ε. The solid and dashed curves here have the same significance as in Fig. 2. In the given situation, a singularity of the isentropic model as $\varepsilon \to 0$ is the fact that the centered wave to the right of the plate degenerates into the characteristic curve. Here, obviously, $u_f \to u_+$. It is evident from Figs. 2 and 3 that the disparity between the results obtained using conditions (2) and (3) increases with a decrease in ε. In the centered wave contiguous with the front the first Riemann invariant is preserved, i.e., $u + 2a/(\varkappa - 1) = r_+ \equiv u_+ + 2a_+/(\varkappa - 1)$. Consequentely, at the front, where $a_f = 0$, we have $u_f = r_+$. In the isentropic expansion scheme, i.e., with the application of condition (2), as the perforation ratio is decreased ($\varepsilon \to 0$) the sound velocity tends to zero, and u_+ tends to the maximum steady flow velocity. Inasmuch as a_+ enters into r_+ with the large factor $2/(\varkappa - 1)$, the decrease of a_+ prevails, and within the framework of (2) u_f decreases as $\varepsilon \to 0$. On the other hand, by condition (3) the entropy s_+ exceeds $s_m = s_-$, the excess increasing with decreasing value of ε. For this reason, even though u_+ increases more slowly with decreasing ε than in the case (2), this process is offset by the slower decrease of the sound velocity a_+, which remains finite as $\varepsilon \to 0$. This is the reason for the slight increase of u_f with decreasing perforation ratio. Of course, sudden expansion without the inception of compression shocks and, as a result, without any increase in entropy is impossible, although for $\varepsilon \leqslant 0.05$, where experimental confirmation of the validity of (3) is lacking, the increase in the entropy can be much smaller than implied by the indicated condition. Moreover, with a decrease in ε the effects of rarefaction of the gas will inevitably begin to be felt. All this requires an extremely cautious attitude toward the results obtained as $\varepsilon \to 0$.

In conclusion, we discuss the difference of the problem solved here from the problems treated in [2, 3]. The work reported in [2] was concerned with the unsteady flow of gas into vacuum through a semipermeable screen. In that work, of the conditions used above, only the first Eq. (1), i.e., the condition of conservation of mass flow, was used. On the other hand, the total enthalpy and entropy of the gas vary during its flow through the screen in accordance with a scheme involving the following considerations. First, it is assumed that the mass flow of gas $q \equiv (\rho u)_\pm$ is proportional to the differential pressure, i.e., $q = \alpha(p_- - p_+)$ with a constant proportionality factor α. In the case of a perforated panel or wall, the given relation with α depending on ε can only be used for subsonic flow, which, however, does not occur in flow into vacuum. Second, in [2], in the two-parameter set of solutions with $0 \leqslant M_- \leqslant 1$ and $M_+ \geqslant 1$ ($M = u/a$ is the Mach number) the parameter is chosen for which regions of sub- and supersonic flow do not exist to the left and right of the screen, i.e., $u_\pm = a_\pm$. The latter must clearly be regarded as a property of the screen. In the problem discussed above, $u_\pm = a_\pm$ only in the absence of the plate (for ε = 1).

Finally, in the model proposed in [3] for the unsteady flow of a gas into vacuum through a perforated plate it is assumed that the parameters p_m, ρ_m, u_m realized in the critical cross section of the perforation are the same as would occur for flow created by acceleration of the undisturbed gas in a transient rarefaction wave with subsonic velocity. To the left of the plate in this case is a region of subsonic flow with constant parameters. The intensity of the rarefaction wave propagation through the rest gas is determined from the condition of equality of the mass flow rates before the plate and in the critical cross section. In the region after the plate, as in [2], it is assumed that a flow region with constant parameters does not exist, i.e., $u_\pm = a_\pm$. The system of relations at the plate is formulated in two ways. The first presupposes satisfaction of the two conditions (1) relating the cross sections m and +. However, the total enthalpy in the cross sections – and + can differ. The second approach is based on replacement of the second Eq. (1) by the momentum conservation principle

$$\varepsilon(p+\rho v^2)_m - \varepsilon\Delta p = (p+\rho v^2)_+.$$

Here the influence of fluid friction of the plate is introduced by the formula $\Delta p = \beta q\sqrt{T_0}$ with the fluid friction coefficient β and the temperature of the undisturbed gas T_0.

We note that, in contrast with [1], in [2, 3] experimental confirmation is not given in support of the assumptions underlying these studies.

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PRESSURE FLUCTUATIONS DURING FLOW AROUND BLUNT BODIES

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At subsonic flight speeds the most intense vibrations develop during flow separation and the formation of local supersonic zones, while at supersonic speeds they occur in the interaction of a shock with the boundary layer. The combination of intense pressure fluctuations and a relatively large velocity head at transonic speeds can lead to appreciable dynamic loads, and the abrupt rearrangement of the character of the flow changes the aerodynamic characteristics. We present data which illustrate some forms of fluctuating loads developing on aircraft components at both subsonic and supersonic flight speeds.

1. Experimental Procedure. A cylindrical model of diameter d = 50 mm and length l = 200 mm was tested by mounting it at right angles to the flow on thin side plates fastened to the lower perforated wall of a wind tunnel. Measurements were made when the model was rotated about its axis by an angle φ. A spherical model of diameter 70 mm mounted on a base 15 mm in diameter was tested also. Pressure fluctuations on the spherical model were measured with three inductive pressure transducers. The angle φ was measured by the rotation of the model support.

The tests were performed in an intermittent type wind tunnel whose test section was 600 × 600 mm in cross section. The Reynolds numbers, determined from the free-stream parameters and the diameter of the sphere, were in the range $Re_d = (0.6-1.5)\cdot 10^6$.

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