BRIEF COMMUNICATIONS

FEATURES IN THE PROPAGATION OF A SUPERSONIC FAN-SHAPED JET

V. I. Pogorelov and G. B. Shcherbanina

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We present a scheme for the calculation of a fan-shaped jet formed on collision of supersonic oppositely directed underexpanded jets. A comparison with experiment is offered.

A supersonic fan-shaped jet is formed on collision between two identical underexpanded gas jets directed at each other, and the flow which is generated is symmetrical relative to the plane of interaction, i.e., the plane in which the jets collide. In the following we will consider only half of the flow. The qualitative flow pattern in such a jet can be described in the following manner (Fig. 1). As the supersonic jet impinges on the plane of interaction, a curvilinear jump I is formed ahead of the plane (Fig. 1). If the distance between the plane of interaction and the nozzle outlet is small, the compression shock will appear directly at the boundary of the jet (point T), since the intensity of the hanging compression shock of the free jet is small. With increasing distance separating the nozzle outlet and the plane of interaction, the intensity of the hanging compression shock increases, thus causing it to interact with the curvilinear compression shock. As a result we have a triple configuration of the shock waves at point T (Fig. 1b). In this case, the reflected shock wave TB appears at the boundary. The coordinate of the point of flexure for the jet boundary determines the exit cross section of the fan-shaped jet. Flow in such a jet is supersonic and we use the well-studied method of characteristics to calculate such a jet [1, 2].

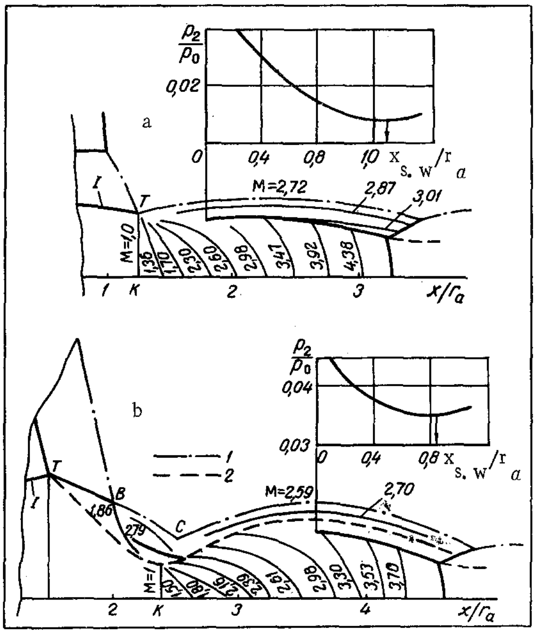

Fig. 1. Flow field in a fan-shaped jet (M_a = 1.905, n = 6.1, α = 3°, k = 1.4): a) l/r_a = 0.96; b) 3.25; 1) jet boundary; 2) slip line.

To determine the subsonic flow in the region between the plane of interaction and the curvilinear compression shock we assume that the flow in that region is one-dimensional. The Mach number is equal to its value behind the compression shock, while the stagnation pressure at the cross section is equal to the mean arithmetic value between the magnitude of the pressure behind the curvilinear shock and at the plane of interaction.

When the curvilinear compression shock reaches the jet boundary, it is assumed that the Mach number behind the shock wave is equal to unity, and that the direction of the velocity vector at the exit cross section of the fan-shaped jet varies linearly from the value behind the shock wave to the value at the plane of interaction (Fig. 1a).

The position of the point T at the jet boundary (Fig. 1a) is determined after the flow rate in the cylindrical cross section TK has been equated to the flow rate of the gas from the nozzle.

Somewhat more complicated is the calculation of the subsonic region in the second case in which the curvilinear compression shock interacts with the hanging compression shock (Fig. 1b).

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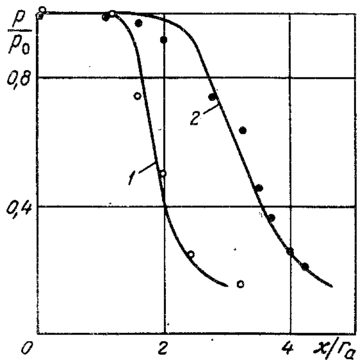

Fig. 2

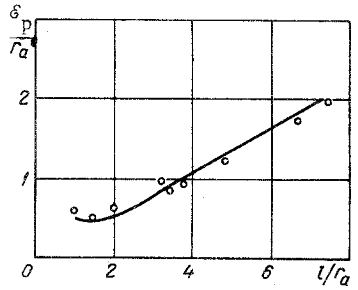

Fig. 3

Fig. 2. Distribution of stagnation pressures behind the normal compression shock on the plane of interaction: 1) theory and experiment for $l/r_a = 0.96$; 2) the same for $l/r_a = 3.25$.

Fig. 3. Location of the triple point T as a function of the distance between the plane of interaction and the nozzle outlet.

With the same hypotheses regarding the one-dimensionality of flow in the subsonic region, the position of the triple point on the hanging shock is determined initially from the condition of the conservation of mass for the gas in front of and behind the shock; this is then followed by the determination of the position of the slip line from the condition that the static pressures on that line are equal. The flow in the region of the subsonic stream between the slip lines and the plane of interaction is regarded as one-dimensional, while the calculation of the supersonic region TB contained between the slip lines and the shock wave (and then the boundary of the fan-shaped jet) is accomplished by the method of characteristics. The position of the point T on the hanging compression shock is assumed to have been properly chosen if the condition $dF/dX = 0$ has been satisfied in the cross section in which the subsonic flow attains the speed of sound, and if the velocity vector at the slip line exhibits an inclination to the plane of interaction that is equal to zero.

The position of the triple point satisfying this boundary condition is determined by the method of iterations.

In addition to the existence of a subsonic region of flow, we can also include the following among the unique features of the results from the calculation.

First of all, it is possible to have a hanging compression shock in a fan-shaped jet, which may be reflected from the plane of interaction – depending on the initial parameters – in a regular or an irregular manner. In the latter case, the position of the triple configuration is determined from the condition of minimum static pressure behind the hanging shock (Fig. 1). As in the case of an axisymmetric jet [3], this method yields good agreement with experiment.

Secondly, the slip line which is formed behind the triple point T (Fig. 1b) passes rather close to the boundary of the fan-shaped jet. If we bear in mind that a small fraction of the flow from the nozzle (~10%) passes through the section TK, we find that virtually all of the gas flow from the nozzle flows into the region enclosed between the boundary of the fan-shaped jet and the slip line.

The boundary of the fan-shaped jet behind its exit section may be broken (point C in Fig. 1b), and two hanging compression shocks may form within the fan-shaped jet.

The intensity of the first hanging compression shock initially increases, and then it diminishes. In Fig. 1b it disappears near the slip line; however, this does not indicate that it is impossible to select a regime in which it will reach the plane of interaction and be reflected from the latter. (The reflection in this case may be regular or irregular.) Figure 1 shows examples of calculations based on this procedure. From these data we can judge the unique characteristics of flow in a fan-shaped jet and, in particular, we can get some idea as to the nature of the distribution for the lines showing the constant Mach numbers.

To test the effectiveness of this method, we compared the calculation results with experimental data. Figure 2 shows a comparison of the stagnation pressures behind the normal compression shock in the plane of interaction with the values measured by means of a Pitot tube during the experiment. These pressures are referred to the stagnation pressure in the plane of interaction. The segment of the curve for which $p/p_0 = 1$ corresponds to the subsonic region of flow.

Figure 3 shows the theoretical curve and the experimental data for the position of point T as a function of the distance between the nozzle outlet and the plane of interaction.

Having analyzed the theoretical and experimental data, we can state that the proposed calculation scheme is quite effective and can be used in engineering practice.

NOTATION

M	is the Mach number;
p	is the pressure;
$n = p_a/p_n$	is the ratio denoting the extent to which the jet does not meet specifications;
r_n	is the pressure in the ambient medium;
k	is the adiabatic exponent;
α	is the half-angle of nozzle divergence;
r_a	is the radius of the nozzle exit section;
l	is the distance between the nozzle outlet and the plane of interaction;
ε_p	is the distance from the point of interaction between the curvilinear compression shock and the hanging shock or the distance between the boundary of the free jet and the plane of interaction.

All of the linear dimensions have been referred to the radius of the nozzle exit section.

Subscripts

a	denotes the parameters at the nozzle outlet;
0	denotes the stagnation parameters;
2	denotes the gas parameters behind the hanging compression shock of the fan-shaped jet.

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