SUPERSONIC INVISCID FLOWS WITH THREE-DIMENSIONAL INTERACTION OF SHOCK WAVES IN CORNERS FORMED BY INTERSECTING WEDGES

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Results of numerical and analytical investigations of inviscid steady supersonic flows in corners formed by intersecting wedges are presented. Despite the great number of papers dealing with such flows, many features of the formation of complex systems of spatially interacting shock waves in corner configurations have not been adequately studied. Some of these problems are investigated in the present paper by consideration of the generic corner flows, which are conical and symmetric about the bisector plane of a corner. These flows are numerically calculated by solving three-dimensional steady Euler equations with a marching method. Effects of the angle of inclination of the corner surfaces to the free stream direction, sweep angle of the leading edges and the dihedral angle of the corner are discussed.

Transition from regular to irregular reflection of shock waves

In the corner flows considered, planar shock waves generated by corner wedges intersect and reflect at the bisector plane. Both regular reflection (RR) and irregular (IR) or Mach reflection (MR) of these shock waves are possible [1-7]. It is very important, both for theory and applications, to determine the boundaries of domains of the regular and irregular reflections. In particular, this problem for the case of conical flows in corners was considered in [1-3], but the data obtained are contradictory.

Different criteria of the transition from regular to Mach reflection (TRM) in two-dimensional flows are well known (see [8]). First, this is the detachment criterion (DC) determined by the maximal angle $(\theta_w)_D$ of flow deflection behind the incident shock wave (*i*-shock wave), at which the flow behind the reflected shock wave (*r*-shock wave) can still return to the flow direction in front of the *i*-shock wave. Regular reflection is theoretically impossible for wedge angles $\theta_w > (\theta_w)_D$. The second, named sonic, criterion (SC) is determined by the condition that the flow velocity behind the *r*-shock wave is sonic. The corresponding wedge angle $(\theta_w)_S$ differs from $(\theta_w)_D$ by no more than fractions of a degree within the entire range of Mach numbers. The third criterion, the so-called mechanical equilibrium or von Neumann criterion (vNC), is proposed (see [8]) for reflection conditions possible only at Mach numbers greater than a certain value, $M > M_* \approx 2.2$. The corresponding wedge angle $(\theta_w)_N$ is determined by the condition that the pressure behind the *r*-shock wave is equal to the pressure behind the normal *i*-shock wave. Two solutions, RR and MR respectively, are theoretically possible for $M > M_*$ and $(\theta_w)_N < \theta_w < (\theta_w)_D$. In unsteady flows with reflection of a moving shock wave from a wedge, the RR solution unambiguously realizes in this domain, that is, either the S or D-criteria determine transition to MR in this case [8]. It has been recently established (see review [10]) the TRM in two-dimensional steady flows at $M > M_*$ is accompanied by a hysteresis. In experiments, the transition to an MR occurs at a certain θ_w between $(\theta_w)_N$ and $(\theta_w)_D$ as the wedge angle increases, depending on the level of flow disturbances in the test facility, but the back transition to an RR occurs near $(\theta_w)_N$ as the wedge angle decreases. In a wind tunnel with a low level of flow disturbances or in a numerical experiment with no disturbances at all, the transition to Mach reflection occurs in accordance with the DC or SC.

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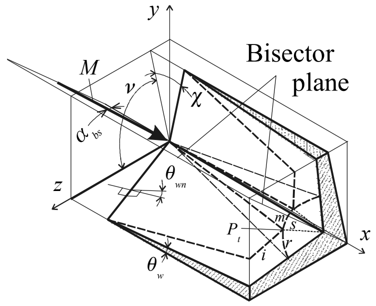

Fig. 1. A sketch of a corner configuration.

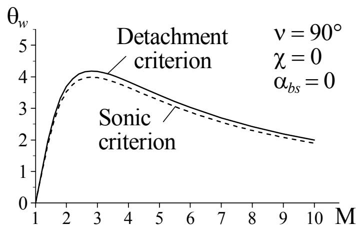

Fig. 2. Corner wedge angles corresponding to the S and D-criteria of TRM.

The same two-dimensional TRM-criteria may be assumed to be valid in problems of spatial interaction of planar shock waves generated by wedges in the corner configurations considered. In the present work, the corresponding to these criteria angles of flow deflection at reflection of shock waves at the bisector plane of a corner are deter-mined by solution [10] of a problem on a planar shock wave generated by a yawed wedge in a uniform supersonic flow. This three-dimensional problem has been reduced in [10] to an equivalent problem for the two-dimensional flow in a plane normal to the leading edge of the considered yawed wedge. The Mach number of the equivalent two-dimensional flow is determined by a projection of the free-stream velocity on the normal plane. The problems of interaction of two planar shock waves in a space or yawed reflection of a planar shock wave at a plane surface amount to solution of two sequential problems on determination of a shock wave generated by a yawed wedge.

A sketch of a corner configuration with definition of its parameters is shown in Fig. 1. A configuration which has the leading edges of a sweep angle $\chi = 0$ and an angle between them $\nu = 90°$ (in the plane "*zy*") is considered usually. The free stream is assumed to be directed along the *x*-axis (with no angle of attack in the bisector plane $\alpha_{bs} = 0$, see Fig. 1), and the change in flow regimes derives from the change in the wedge angle θ_w ($\theta_w = \theta_{wn}$ at $\chi = 0$, here the angle θ_{wn} is defined in a plane normal to the leading edge). Note, a change in θ_w involves a change in the dihedral angle between wedge surfaces and, respectively, conditions for the corner flow as a whole are changed.

The results of analytical calculations for the typical corner configuration show that the Mach number component M_n normal to the line of intersection of the shock waves does not exceed M_* even in the limit, as $M \to \infty$. Thus, the transition from regular to Mach reflection in this case should occur in accordance with the S or D-criterion. The wedge angles $(\theta_w)_D$ and $(\theta_w)_S$ obtained from these criteria are plotted in Fig. 2 as functions of the Mach number. As well as the two-dimensional flow, the transition boundaries determined by the S and D-criteria for the corner flows differ by fractions of a degree. The maximum value $(\theta_w)_D \approx 4.185°$ is reached for a Mach number about $M \approx 2.8$. Note, the boundary obtained using the D-criterion differs from that determined in [1]. In particular, based on the data of [1], the angle $(\theta_w)_D$, which is maximum for a Mach number $M \approx 3$, is equal to $(\theta_w)_D \approx 8°$. For $M \geq 5$, this boundary is close to that obtained in [3], but there is a difference in the interval M = 1.5-4, where the maximum value of the transition wedge angle is reached. In [3], this value is approximately by a degree greater than it is in the present work.

The analytical study of TRM boundaries was supplemented by direct numerical computations. For the corner flow considered, three-dimensional steady Euler equations were solved by a marching method. A high-order TVD scheme described in [11] was used. The fluxes at the faces between the cells were computed using the HLLE Riemann solver, and integration along the longitudinal (marching) coordinate was performed by the Runge – Kutta method.

Computations were performed for M = 1.5, 3, 6, and 10 with varying the wedge angle in a vicinity of transitional values with a 0.5° step. The onset of an MR-type flow regime with increasing the wedge angle and, hence, a transition wedge angle was determined, first, visually on the basis of the computed cross-flow fields. Theoretically, slip lines should come out from triple points of the Mach wave configuration. In numerical calculations, these slip lines are manifested as layers with a drastic transverse change in density. As in [12], the flow patterns were visualized by the "numerical schlieren" technique, which captures density gradients. The computed cross-flow patterns were used to determine the characteristic size of the Mach stem. It was specified, in a cross section $x = \text{const}$, by the angle φ_t between the radius-vector of the triple point P_t of the Mach configuration and the bisector. From the data on φ_t values obtained for a series of angles θ_w at a given Mach number, the transition wedge angle was also determined by extrapolating the φ_t value to $\varphi_t = 0$, that is, by the intersection of the curve approximating the φ_t values and the θ_w-axis. A cubic polynomial approximation by the least-squares technique was performed. As a whole, the computed transition wedge angles correspond to the analytical dependences, though the accuracy of this "numerical" determination of the transition does not show definitely which, the S or D-criterion, is responsible for the transition (the difference between them is less than 0.3°).

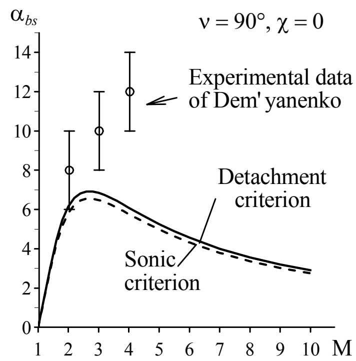

Fig. 3. Angles of attack in the bisector plane corresponding to the S and D-criteria of TRM.

Another corner configuration, which had been earlier experimentally studied in [2], was also considered in the present work. This configuration differs from the previous typical one by the fact that it has $\theta_w \equiv 0$ and the corner flow in it is determined by the free-stream angle of attack α_{bs} in the bisector plane (see Fig. 1) rather than changing wedge angles. Therewith, the dihedral angle of the corner remains the same. The results of analytical calculations of the angles α_{bs} corresponding to the S or D-criterion of TRM for such a corner configuration with $\nu = 90°$, $\chi = 0$ are plotted in Fig. 3. The same figure shows the experimental data of [2] obtained for Mach numbers M = 2.03, 3.02, and 4.03 in the T-313 wind tunnel based at ITAM. The experimental transition values of α_{bs} were obtained with an error up to ±2°, they are higher than the calculated values by 2-6°, are monotonically increasing, and have no maximum within the Mach number range examined. One of the reasons of the above disagreement is the displacing effect of the boundary layer, which was artificially tripped in the experiments of [2]. As might be deduced from the data [2], the effect of shock wave displacement in RR flow regimes, as compared to shock wave positions in the inviscid flow, is equivalent to an increase in the angle α_{bs} by 2°÷3°. In addition, behavior of experimental transition angles α_{bs} depending on the Mach number is related to the character of interaction of reflected shock waves with the boundary layer on the plane surfaces. These shock waves are glancing relative to the surfaces and can induce three-dimensional (oblique) separation of the boundary layer. The numerical results show that the intensity of the reflected shock waves is lower than the critical value for oblique separation of the turbulent boundary layer for M = 2 and exceeds it for M = 3 and 4.

Types of supersonic conical flows with irregular reflections of shock waves

The numerical study conducted for flows in corners with $\nu = 90°$, $\chi = 0$ shows that types of irregular reflections of shock wave forming in cross flows in these corners are the same, which are typical of irregular reflections in two-dimensional pseudo-steady flows [8]. Namely, von Neumann reflection (vNR), single (SMR), transitional (TMR), and double (DMR) Mach reflections occur. Note, in contrast to that, only the SMR type is possible in two-dimensional steady flows [8]. Numerical calculations of SMR-type conical flows in corners have been known for a long time [4-6]; TMR and DMR types have been also obtained numerically in [7]. However, these studies include no analysis of the flow regimes with the use of shock polars, a comparison to IR types arising in two-dimensional flows did not carried out, and the computed flow regimes were not identified as indicated above.

Typical flow patterns obtained by the "numerical schlieren" technique are pictured below in the conical coordinates y/x, z/x. Flow patterns are accompanied with analytical shock polars presented in the coordinates (p/p_∞, θ_n), where p/p_∞ is the pressure behind the incident (i) or reflected (r) shock wave normalized to the free-stream pressure p_∞, and θ_n is the angle of flow deflection in the plane perpendicular to the line of intersection of the i- and r-shock waves. The i-r-polar combinations are given for two planes of shock wave reflection or interaction: first, for the bisector plane ($\varphi_t = 0$), and second, for the meridian plane ($\varphi_t > 0$) passing through the x-axis and the triple point P_t of the IR configuration obtained numerically. The i-r-shock polars for $\varphi_t > 0$ are given because the following reason. If one considers a corner flow in the conical coordinates, the triple point, with the evolution of an IR configuration, moves away from the bisector but remains on the i-shock wave, and the radius-vector of this point increases. Therewith, the cross-flow velocity upstream of the triple point and the slope of the i-shock wave to this velocity decrease. Consequently, by virtue of the corner flow conicity, the behavior of the i-r-polar combinations, determining which IR configuration comes into being, for a case of $\varphi_t > 0$ differ from those for $\varphi_t = 0$.

An example of a flow with the irregular reflection of vNR-type is shown in Fig. 4a for $M = 1.5$ $\theta_w = 5°$; the shock wave polars are plotted in Fig. 4b. In both cases of $\varphi_t = 0$ and $\varphi_t = 5.5°$, the r-shock polar is on the right of the p/p_∞ axis and never intersects the i-shock polar. The situation is similar to that for the von Neumann reflection of weak shock waves in two-dimensional pseudo-steady flows [8]. The same vNR-type of irregular reflection is observed in the considered corner flows if the r-shock polar intersects the i-shock polar on the right of the r-shock polar centerline, as it takes place in two-dimensional pseudo-steady flows.

An example of a flow with the SMR-type of shock wave reflection and its i-r-polar combinations are shown in Fig. 5a and 5b for $M = 3$, $\theta_w = 10°$. The i-shock and r-shock polars intersect on the left of the centerline of the latter. For the MR configuration obtained numerically ($\varphi_t = 4.1°$), the point of intersection (the triple point P_t) lies on the r-shock polar higher than the point P_s, for which the post-shock velocity component, which is normal to the line of intersection of the i-shock and r-shock waves, is sonic. This corresponds to conditions for two-dimensional flows in which the SMR occurs [8]. Note, the analysis of the properties of SMR configurations forming in corner flows shows that, in a cross section, the Mach stem can be convex, concave, and also rectilinear, in contrast to two-dimensional steady flows with SMR, where the Mach stem is always concave. For instance at $M = 3$, the rectilinear Mach stem forms for $\theta_w \approx 13°$.

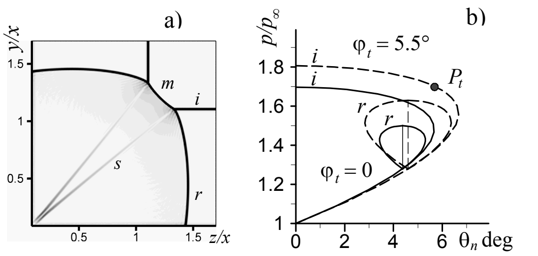

Fig. 4. Cross flow pattern of vNR-type (a) and shock wave polars (b) for $M = 1.5$, $\theta_w = 5°$, $\nu = 90°$, $\chi = 0$.

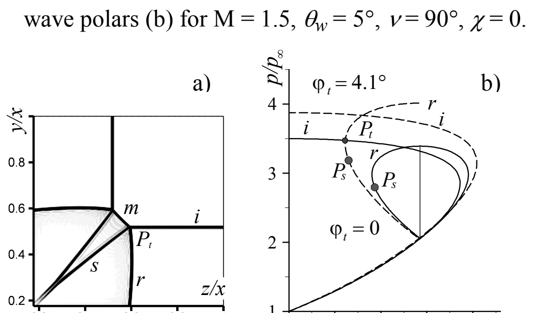

Fig. 5. Cross flow pattern of SMR-type (a) and shock wave polars (b) for $M = 3$, $\theta_w = 10°$, $\nu = 90°$, $\chi = 0$.

TMR- and DMR types of shock wave reflection in two-dimensional pseudo-steady flows around a wedge form if the flow behind the reflected shock wave near the triple point P_t

becomes sonic or supersonic, and some portion of this shock wave emanating from the triple point is rectilinear. A typical feature of these reflection types is the fact that the slip lines s emanating from the triple points P_t incident on the wedge; approaching the wedge, the slip lines turn counter the free stream and coil up in spiral curls. In the DMR-flows, deceleration of the supersonic flow behind the reflected r-shock wave results in the formation, at a certain distance from the triple point of the main Mach stem m, of another three shock wave system with a triple point P_{t1}. This wave system includes the reflected r-shock wave, the strong rr-shock wave which incidents on the coiling slip line, and the secondary Mach stem m_1. In the TMR-flows, a centered compression wave forms instead of the rr-shock wave.

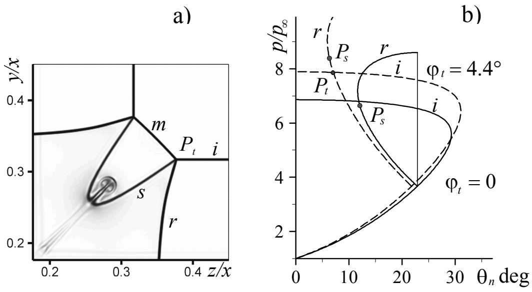

Fig. 6. Cross flow pattern of TMR-type (a) and shock wave polars (b) for M = 6, $\theta_w = 10°$, $\nu = 90°$, $\chi = 0$.

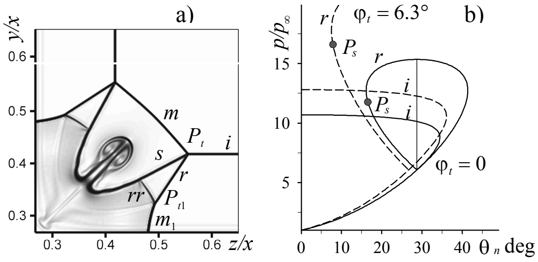

Fig. 7. Cross flow pattern of DMR-type (a) and shock wave polars (b) for M = 6, $\theta_w = 15°$, $\nu = 90°$, $\chi = 0$.

The structure of DMR-type corner flows is similar. The numerical study shows that a rather wide range of flow regimes intermediate between SMR and DMR types should be classified as corner conical flows with the reflection of incident shock waves of TMR-type. In these flows, the stream behind the reflected r-shock wave is also transversely supersonic in a close vicinity of the triple point but it becomes subsonic at a distance from it, and the r-shock wave becomes more and more concave. This curving the r-shock wave is caused by compression waves, but the latter are not centered as in a two-dimensional flow. Nevertheless, the slip lines emanating from the triple points also coil up in spiral curls. Examples of TMR- and DMR-type corner flows are shown for M = 6, $\theta_w = 10°$, Fig. 6, and $\theta_w = 15°$, Fig. 7. In both cases, the flow behind the reflected shock wave at the triple point is supersonic in the transverse direction. Besides, the r-shock polar and i-shock polar intersect lower than the point P_s corresponding to the post-shock velocity whose component normal to the line of inter-section of the shock waves is sonic.

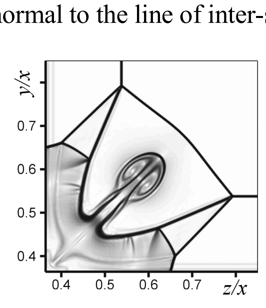

Fig. 8. Cross flow pattern of MsMR-type for M = 6, $\nu = 90°$, $\chi = 0$, $\theta_w = 20°$.

The numerical study of corner flows at high velocities $M \geq 6$ shows that a verity of MR-type reflections exists, which may be called MsMR (Multi-shock-wave Mach Reflections). An example of a corner flow of this type is shown in Fig. 8 for M = 6, $\theta_w = 20°$. These flow patterns appear if the flow behind the reflected shock wave is transversely supersonic, but the free-stream velocity component normal to the line of inter-section of the i-shock waves is greater than in flows of DMR-type. In a cross flow of MsMR-type, flow deceleration with multiple reflections of shock waves occurs in the stream between the triple points P_t and P_{t1}. This similar to that observed in the case of flow deceleration in two-dimensional inlets from supersonic velocities at the entrance, with a transition through transonic

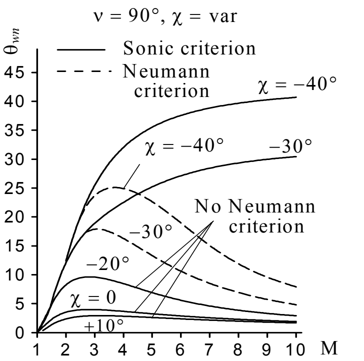

Fig. 9. Transition wedge angles for corner configurations with different sweep angles.

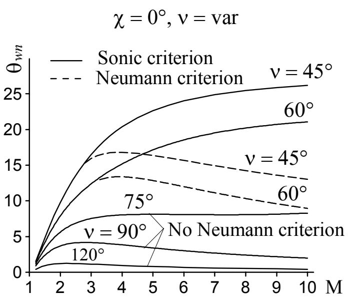

Fig. 10. Transition wedge angles for corner configurations with different dihedral angles.

velocities in the throat, to subsonic velocities behind the throat.

Types of supersonic conical flows forming in corners with various dihedral and sweep angles

The effects of the sweep angle of the leading edges and the dihedral angle of the corner on TRM boundaries were studied in the present work. Note, that the dihedral angle for an arbitrary corner configuration is defined by an angle ν between the projections of the leading edges on the plane "*zy*", see Fig. 1. Previously unknown parameters of corner configurations were determined for which the transition in accordance with the vN-criterion is possible. The wedge angles $(\theta_{wn})_{\mathrm{D}}$ and $(\theta_{wn})_{\mathrm{N}}$ corresponding to the D- and vN-criteria for a number of sweep and dihedral angles are presented in Figs. 9 and 10 versus the Mach number. It should be noted that the transition in accordance with vN-criterion is possible beginning from a certain sweepforward angle $\chi < -20°$ for $\nu = 90°$ and an acute dihedral angle $\nu < 75°$ for $\chi = 0$. Obviously, there is a domain of various combinations of corner sweepforward and acute dihedral angles providing this transition.

The main features of flow patterns changing with varying the wedge angle θ_{wn} under the said conditions are shown for M = 6 $\nu = 90°$, $\chi = -30°$, $\theta_{wn} = 10°$, 12.5°, and 15°, Fig. 11, and $\nu = 45°$, $\chi = 0°$, $\theta_{wn} = 10°$ and 12°, Fig. 12.

In the case of $\nu = 90°$, $\chi = -30°$, reflections of the *i*-shock waves of RR-type form at angles $\theta_{wn} \le (\theta_{wn})_{\mathrm{N}} \approx 10.61°$ and also at a greater angle $\theta_{wn} = 12.5°$, which is significantly smaller than the angle $(\theta_{wn})_{\mathrm{D}} \approx 27.42°$ determined by the D-criterion. Irregular reflections of DMR or MsMR-type form at angles $\theta_{wn} = 13°$ and 15°, which are larger than the angle $(\theta_{wn})_{\mathrm{N}}$ but significantly smaller than the angle $(\theta_{wn})_{\mathrm{D}}$. In the case of $\nu = 45°$, $\chi = 0°$, RR-type reflections of the *i*-shock waves are observed at angles $\theta_{wn} \le 11°$, whereas flows with DMR or MsMR-type reflections form at an angle $\theta_{wn} = 12°$, which is noticeably smaller than $(\theta_{wn})_{\mathrm{N}} \approx 15.67°$, and correspondingly, at greater angles $\theta_{wn} > 12°$. The computations of corner flows for parameters M = 6, $\chi = 0°$, $\nu = 60°$ show that RR-type

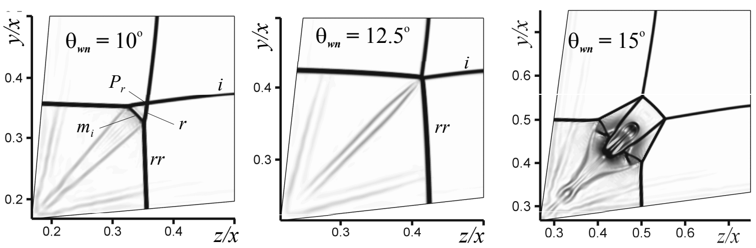

Fig. 11. Cross flow patterns for swept corner configuration $\nu = 90°$, $\chi = -30°$, M = 6.

reflections of the i-shock waves are observed at $\theta_{wn} \le 11°$, whereas flows with DMR or MsMR-type reflections form at $\theta_{wn} = 12°$ close to $(\theta_{wn})_N \approx 12°$ and, correspondingly, at greater angles. It should be noted that, in the considered flow regimes with regular reflection of i-shock waves, a cross flow pattern occurs which includes an internal strong shock wave with Mach stem m_i that forms behind a portion of flow with the regular reflection of the i-shock waves. One can see this for $\theta_{wn} = 10°$ in both cases of the swept corner configuration with $\chi = -30°$ at $\nu = 90°$, Fig. 11, and the configuration with a dihedral angle $\nu = 45°$ at $\chi = 0°$, Fig. 12. Since these reflections include a regular reflection of the main incident shock waves generated by the wedges and an irregular reflection of post shock waves, they may be called combined regular-irregular reflections or a post Mach reflections.

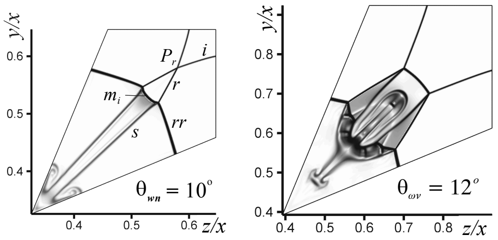

Fig. 12. Cross flow patterns for corner configuration with a dihedral angle $\nu = 45°$, $\chi = 0$, M = 6.

The computations show that, as the wedge angle increases, flows with such a reflection of shock waves form until the internal Mach stem m_i reaches the point P_r of regular reflection of the i-shock waves. At greater wedge angles, this flow patterns "break down", and DMR or MsMR-types reflections of the incident wedge-attached shock waves occur. The computations also show that, with reverse changing the sweep and dihedral angles to certain values $\chi > 0$ at $\nu = 90°$ or $\nu > 90°$ at $\chi = 0$, one can obtain the shock wave reflections of SMR and vNR types already discussed. Thus, a spectrum of irregular reflection types obtained for flows in corners of sweepforward angles $\chi < 0$ and acute dihedral angles $\nu < 90°$ is more broad in comparison to the corner configurations of sweepback angles $\chi \ge 0$ and rectangular or obtuse angles $\nu \ge 90°$ but it includes those ones analyzed for the latter case.

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