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NASA TM-77920

DECELERATION OF A SUPERSONIC FLOW BEHIND A CURVED SHOCK WAVE WITH ISOENTROPIC PRECOMPRESSION

V. G. Dulov, V. A. Shchepanovskiy

Translation of "Tormozheniye sverkhzvukovogo potoka za krivolineynoy udarnoy volnoy s predshestvuyushchim izoentropicheskim szhatiyem," Academy of Sciences of the Soviet Union, Sibirskoye otdeleniye, Izvestiya, Seriya Tekhnicheskikh Nauk, No. 8, June 1977, pp. 72-78 (78A-18986) (UDC 533.6.001.55:)

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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      85N35164*#   ISSUE 24   PAGE 4061   CATEGORY 2   RPT#: NASA-TM-77920 NAS
      1.15:77920   CNT#: NASW-4006   85/09/00  13 PAGES   UNCLASSIFIED DOCUMENT
      Original language document was announced in IAA as A78-18986
UTTL: Deceleration of a supersonic flow behind a curved shock wave with
      isentropic precompression
AUTH: A/DULOV, V. G.;  B/SHCHEPANOVSKIY, V. A.
CORP: National Aeronautics and Space Administration, Washington, D.C.
      AVAIL.NTIS
SAP:  HC A02/MF A01
CIO:  U.S.S.R. Transl. by The Corporate Word, Inc., Pittsburgh, Pa.   Transl.
      into ENGLISH from Sibirsk. Otd., Izv. Ser. Tekhn. Nauk (USSR), no. 8, Jun.
      1977  p 72-78
MAJS: /*COMPRESSIBILITY EFFECTS/*DECELERATION/*SHOCK WAVE PROFILES/*SUPERSONIC
      FLOW
MINS: / IDEAL FLUIDS/ ISENTROPIC PROCESSES/ PRESSURE DROP/ VORTICES
ABA:  P.T.H.
ABS:  Three-dimensional supersonic flows of an ideal fluid in the neighborhood
      of bodies formed by being cut out along the streamlines of an axisymmetric
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1. Report No. NASA TM-77920	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle DECELERATION OF A SUPERSONIC FLOW BEHIND A CURVED SHOCK WAVE WITH ISOENTROPIC PRECOMPRESSION	5. Report Date SEPTEMBER 1985 6. Performing Organization Code
7. Author(s) V. G. Dulov, V. A. Shchepanovskiy	8. Performing Organization Report No. 10. Work Unit No.
9. Performing Organization Name and Address The Coporate Word 1102 Arrott Building Pittsburgh, PA 15222	11. Contract or Grant No. NASW-4006 13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Translation of "Tormozheniye sverkhzvukovogo potoka za krivolineynoy udarnoy volnoy s predshestvuyushchim izoentropicheskim szhatiyem," Academy of Sciences of the Soviet Union, Sibirskoye otdeleniye, Izvestiya Seriya Tekhnicheskikh Nauk, No. 8, June 1977, pp. 72-78. (78A-18986) (UDC 533.6.001.55:)

16. Abstract

Three-dimensional supersonic flows of an ideal fluid in the neighborhood of bodies formed by being cut out along the streamlines of an axisymmetric flow are investigated. The flow consists of a region of isoentropic compression and a region of vortex flow. An exact solution with variable entropy is used to describe the flow in the vortex region. In the continuous flow region an approximate solution is constructed by expanding the solution in a series in a small parameter. The effect of the shape of the excission and the vorticity of the flow on compression of the jet and the total pressure loss coefficient is studied.

17. Key Words (Selected by Author(s))	18. Distribution Statement THIS COPYRIGHTED SOVIET WORK IS REPRODUCED AND SOLD BY NTIS UNDER LICENSE FROM VAAP, THE SOVIET COPYRIGHT AGENCY. NO FURTHER COPYING IS PERMITTED WITHOUT PERMISSION FROM VAAP.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	13	

N85-35164#
N-155,648
NASA-HQ

A78-18986#

DECELERATION OF A SUPERSONIC FLOW BEHIND A CURVED SHOCK WAVE WITH ISOENTROPIC PRECOMPRESSION

V.G. Dulov, V.A. Shchepanovskiy

This study investigates three-dimensional supersonic flows of an ideal fluid in the neighborhood of bodies formed by an excision along the streamlines of an axisymmetric flow. The uneven flow consists of two regions: regions of isoentropic compression and regions of vortex flow. An exact solution with variable entropy [1] is used to describe the flow in the vortex region. In the continuous flow region an approximate solution is constructed by expanding the solution in a series according to a small parameter. The effect of excision shape and flow vorticity on jet compression and the total pressure loss coefficient is studied. /72*

1. Reference [1] investigates solving axisymmetric equations for an ideal gas with variable entropy. This flow is described with a common differential equation for characteristic function z(h):

$$z'' = -z'\frac{az'^2 + h\left[\frac{2\alpha}{\varkappa} + 4(\alpha-1)\right]zz' - \frac{2}{\varkappa-1}z^2 + \frac{2}{\varkappa-1}h(1-h)}{bz'^2 + \frac{4\alpha(\varkappa-1)}{\varkappa}h^2zz' - hz^2 + h(1-h)},$$

$$a = h(1-h)\frac{4}{\varkappa^2}[\varkappa\alpha(\alpha-1) - \varkappa^2(1+\alpha)^2] + \frac{4(\varkappa-1)}{\varkappa^2}\left[\alpha\varkappa - \alpha^2(\varkappa-1) - \frac{3}{4}\alpha^2\right]h, \qquad (1.1)$$

$$b = \frac{\varkappa-1}{\varkappa}h^2[h(\varkappa\alpha^2 - 4\varkappa\alpha + 3\alpha^2) - 4\alpha\varkappa(\alpha-1)],$$

and total pressure distribution along the streamlines is written as $\rho_0 = C(\Psi_0 - \Psi)^{\alpha}$ (α, c, and Ψ_0 are randonm constants). Here and further all values are given dimensionless form: enthalpy h

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*Numbers in the margin indicate pagination in the foreign text.

relates to heat content h_m, values with velocity dimensionality relate to the maximum velocity of steady outflow in a vacuum $\sqrt{2h_m}$, and pressure relates to total pressure ρ_0. Under these conditions, stream function Ψ should be related to $\rho_0 l/\sqrt{2h_m}$ where l is the characteristic linear dimension.

Flow (1.1) is converted to plane (u, v) of a travel-time curve and physical plane (x, y) with equations:

$$u = z - \alpha\frac{\varkappa-1}{\varkappa}hz', \quad v = \sqrt{1 - h - \left(z - \alpha\frac{\varkappa-1}{\varkappa}hz'\right)^2}, \tag{1.2}$$

$$x = \sqrt{\frac{\Psi_0-\Psi}{p}}\int_{h_0}^{h} F\,dh, \quad y = \sqrt{2\frac{\varkappa-1}{\varkappa}\frac{\Psi_0-\Psi}{p}hz'},$$

$$F = \frac{\left(\frac{\varkappa-1}{\varkappa}hz' - \frac{z''}{\varkappa}\right)u - \frac{1}{\alpha}\left[\frac{1}{2} + u\left(z' - \alpha\frac{\varkappa-1}{\varkappa}hz'' - \alpha\frac{\varkappa-1}{\varkappa}z'\right)\right]}{\sqrt{2\frac{\varkappa-1}{\varkappa}hz'v}}. \tag{1.3}$$

In general, it is impossible to make flow (1.1) adjacent /73
to the even flow by means of a curved shock because the solution is not arbitrary. We will discuss the possibility of joining (1.1) with an even flow through an intermediate region of uneven flow Ω_1 (Figure 1). If this is set up as an exact problem, it can only be solved numerically. To construct an analytic, approximate solution we assume that leading shock AC (See Figure 1) is weak and the flow in Ω_1 is isoentropic. In Ω_2, we have a vortex flow. This flow is described with equation (1.1) and is joined with Ω_1 by means of curved shock wave AB, which diffuses in the uneven flow.

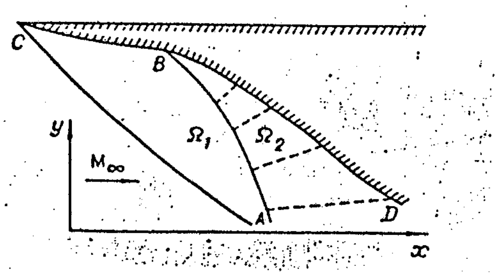

Figure 1

In variables h and ψ, wave AB (see figure 1) can be represented as $h = H(\psi)$. From (1.3), we have the following in the physical plane:

$$x = \sqrt{\frac{(\psi_0 - \psi)^{1-\alpha}}{C} H^{\frac{\varkappa}{\varkappa-1}} I(H)} = x(\psi), \quad I = \int F dh,$$
$$y = \sqrt{\frac{2(\varkappa-1)}{\varkappa} \cdot \frac{(\psi_0 - \psi)^{1-\alpha}}{C} H^{-\frac{\varkappa}{\varkappa-1}}} = y(\psi). \tag{1.4}$$

We use ξ to designate the square of the modulus of velocity in Ω_1; β, ϑ_1, ϑ_2 are the slope of shock wave AB and velocity vectors Ω_1 and Ω_2 to the symmetry axis. Allowing for the fact that the flow in Ω_1 is isoentropic, we can then write the laws of momentum and energy conservation on wave (1.4) as:

$$\xi = (1 - H)\left[\frac{\cos(\beta - \vartheta_2)}{\cos(\beta - \vartheta_1)}\right]^2,$$
$$\mathrm{tg}(\beta - \vartheta_1) = \frac{\varkappa - 1}{\varkappa + 1} \frac{HI(1-H) + \sin^2(\beta - \vartheta_2)}{\sin(\beta - \vartheta_2)\cos(\beta - \vartheta_2)},$$
$$(1 - \xi)^{\frac{\varkappa}{\varkappa-1}} = C(\psi_0 - \psi)^{\alpha} H^{\frac{\varkappa}{\varkappa-1}}\left[1 - \frac{2\varkappa}{\varkappa - 1}\frac{1 - H}{H}\,\mathrm{tg}(\beta - \vartheta_2)\sin(\vartheta_2 - \vartheta_1)\right]. \tag{1.5}$$

The law of conservation of mass is satisfied, since the coordinate of ψ - stream function - is continuous during passage through the shock. The ratio $\mathrm{tg}\beta = y'_{\psi}/x'_{\psi}$ gives the equation for the wave

$$\frac{dH}{d\psi} = -\frac{1-\alpha}{\psi_0 - \psi} \frac{1 - \frac{I}{2}\sqrt{\frac{2\varkappa}{\varkappa-1}\frac{1}{z'H}}\,\mathrm{tg}\beta}{\sqrt{\frac{2\varkappa}{\varkappa-1}\frac{1}{z'H}}\,\mathrm{tg}\beta\left(F - \frac{\varkappa}{\varkappa-1}\frac{I}{2H}\right) - \frac{z''}{z'} - \frac{1}{\varkappa-1}\frac{1}{H}}. \tag{1.6}$$

The set of equations, (1.1), (1.5), and (1.6), and ratio

$$\cos\vartheta_2 = \frac{z - \alpha\frac{\varkappa-1}{\varkappa}z'H}{\sqrt{1-H}}, \tag{1.7}$$

obtained from (1.2) are a closed system of equations for z, H, β, ϑ_1, ϑ_2 and ξ. Solving this system defines flow in Ω_2, the position of shock (1.4) and the distribution of gas dynamics parameters on the wave front.

2. To construct an approximate solution, we must make the transition to travel-time curve variables in the gas flow equations. For problems with axial symmetry, this transition is usually useless when studying exact problems and methods, since the equations become nonlinear. However, this transition can be quite convenient when constructing and analyzing approximate solutions. /74

In the statement for flow isoentropicity, i.e. h = h(p), taken from the Eiler equation transformed to variables $\xi = u^2 + v^2 = 1 - h$, $\eta = v^2 = (1 - h)\sin^2\vartheta_1$, it follows that there is a function $\phi(\xi,\eta)$ such that:

$$\varphi_\xi = \frac{y^2}{2h_p} - \frac{\psi}{2\sqrt{\xi-\eta}}, \quad \varphi_\eta = \frac{\psi}{2\sqrt{\xi-\eta}}. \tag{2.1}$$

Any ϕ selected will satisfy the dynamic equations identically, and from the equation for continuity we obtain the ratios which determine coordinate x:

$$x_\xi = \sqrt{h_p}\,\frac{2(\xi-\eta)\,[\varphi_{\xi\xi} + j(\varphi_\xi + \varphi_\eta)] - \varphi_\eta}{\sqrt{8\eta(\xi-\eta)(\varphi_\xi+\varphi_\eta)}}, \quad x_\eta = \sqrt{h_p}\,\frac{\varphi_\eta + 2(\xi-\eta)\,\varphi_{\xi\eta}}{\sqrt{8\eta(\xi-\eta)(\varphi_\xi+\varphi_\eta)}},$$
$$j = -\frac{h_{pp}}{h_p^2}. \tag{2.2}$$

By excluding X from (2.2) with cross-differentiation, we obtain the equation which contains only one function for ϕ:

$$2(\xi-\eta)\,\eta\,(\varphi_{\xi\eta}^2 - \varphi_{\xi\xi}\varphi_{\eta\eta}) - [(2\xi-\eta)\,\varphi_\eta + 2\xi\varphi_\xi]\,\varphi_{\xi\xi} - 2\eta\,(2\varphi_\xi + 2\varphi_\eta)\,\varphi_{\xi\eta} -$$
$$- \eta\{2[1 - j(\xi-\eta)](\varphi_\xi + \varphi_\eta)\}\,\varphi_{\eta\eta} - 2\xi j\,(\varphi_\xi + \varphi_\eta)^2 + (1 - \eta j)\varphi_\eta(\varphi_\xi + \varphi_\eta) = 0. \tag{2.3}$$

This is a Monzh-Ampere type equation with a quasi-linear part. All terms in the equation contain derivatives from the unknown function as products of two partial derivatives, and coefficients for the products are polynomials according to variable η to no more than the second power. These properties of equation (2.3) make it possible to search for the solution as a series according to the powers of η. We enter the parameter $\varepsilon = \max_{\Omega_1} \eta$

and let

$$\varphi = \sum_{k=0}^{\infty} \varepsilon^k \varphi_k (\xi, \bar{\eta}), \quad \eta = \varepsilon \bar{\eta}. \tag{2.4}$$

Inserting (2.4) in (2.3) gives the following equation for ϕ_k:

$$(2\xi j - 1)\, \varphi_{0,\eta} \left(\varphi_{k,\eta\eta} - \frac{1}{\eta} \varphi_{k,\eta} \right) = F_{k-1}. \tag{2.5}$$

Function F_n is expressed through ϕ_k and their derivatives are expressed with $k \leq n$.

$$\begin{aligned} F_n = {} & (2\xi j - 1)(\varphi_{s,\eta} - \eta \varphi_{s,\eta\eta})\, \varphi_{n-s,\eta} - 2\xi\eta\varphi_{s,\xi,\eta}\varphi_{n-s,\xi\eta} + 2\eta [(1 - 2\xi j)\, \varphi_{s,\xi} + \\ & + \eta j \varphi_{s,\eta} + 2\xi\eta\varphi_{s,\xi\xi}]\varphi_{n-s,\eta\eta} - [2\xi\varphi_{s,\xi\xi} - 2\eta\varphi_{s,\xi\eta} - \eta j \varphi_{s,\eta} - (1 - 4\xi j)\, \varphi_{s,\xi}]\, \varphi_{n-s,\eta} + \\ & + 2\eta\varphi_{s,\eta\xi}\varphi_{n-s,\eta\xi} + (2\xi\varphi_{s,\xi} + \eta\varphi_{s,\eta} - 2\eta^2\varphi_{s,\eta\eta})\varphi_{n-s,\xi\xi} + (4\varphi_{s,\xi\eta} + 2\xi j \varphi_{s,\xi} - \\ & - \eta j \varphi_{s,\eta})\, \varphi_{n-s,\xi}. \end{aligned}$$

Here, repetitive index s indicates summation from 0 to n. If $2\xi j - 1 \neq 0$ (i.e. Mach number $M \neq 1$), formula (2.5) is a recurrent ratio for ϕ_k. Obviously $F_{-1} = 0$. Then, from (2.5), $\phi_0 = A^2 \times \eta^2/2 + B$, where A and B are random functions of ξ. According to (2.1), the flow corresponding to this solution is written with the following formulas:

$$x = \int_{\xi_0}^{\xi} \sqrt{\frac{h_p}{8\xi}} (2\xi j - 1)\, d\xi, \quad y^2 = 2 h_p A^2 \eta,$$

These formulas determine flow in a channel with variable cross- /75
section area in a one-dimensional approximation (isobars for ξ = = const are the straight lines for x = const). Further

$$F_0 = \frac{1}{2 - \xi 2 j} \left\{ \left[\frac{\xi (A^2 - 1)}{A} \left(A'' + \frac{A'^2}{A} \right) + \frac{3 + 2\xi}{2} A A' - 5 j A^2 \right] \eta - \frac{1 + 2\xi j}{\eta} B' \right\},$$

$$\varphi_1 = \frac{1}{1 - 2\xi j} \left\{ [4\xi (A A'' - A'^2) + (5 + 2\xi j) A A' + 3 j A^2] \frac{\eta^3}{3} + [(1 + 2\xi j) B' + 4 B''] \eta \right\}.$$

The flow corresponding to approximate solution $\phi = \phi_0 + \varepsilon \phi_1$ is described with the following equations:

$$x = \sqrt{\frac{h_p}{8\xi}}(A + 4\xi A')\eta + \int_{\xi_0}^{\xi} \sqrt{\frac{h_p}{8\xi}}(2\xi j - 1)d\xi,$$

$$y^2 = 2h_p A^2\eta + \frac{2h_p}{2\xi j - 1}\{[4\xi(AA'' - A'^2) + 4(1 + \xi j)AA' + 3jA^2]\eta^2 + 2(B' + 2\xi B'')\}. \quad (2.6)$$

Here ε is set equal to one, which actually means a return to undeformed variable η. According to (2.6), the isobars are second order curves.

For an rough estimate of approximation process accuracy, we compare it with certain exact solutions for gas flow equations. Since the basic approximation is an expansion according to the angle of flow divergence, a solution in which angle ϑ remains unchanged in the trajectories (i.e. the flow from the gas source. This flow, by the way, has the simplest structure) is the natural choice for comparison.

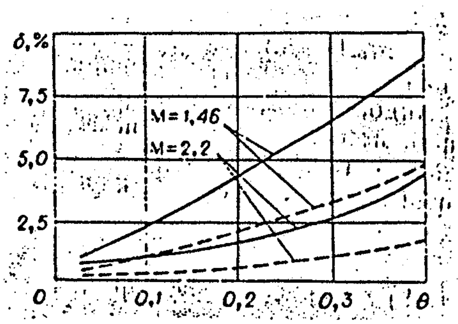

Figure 2

Figure 2 shows graphs of the approximate solutions' relative deviation δ(%) from the exact solution as a function of the angle of cone θ for two Mach numbers at the inlet. Solid lines (x = const) are a one-dimensional approximation and dotted lines are approximation (2.6). As Figure 2 shows, the near-axial region is described most exactly, the second approximation nearly doubles accuracy, and when the Mach number at the inlet (and consequently throughout the entire flow) increases, error decreases.

3. To construct the flow in Ω_1 we use approximate solution (2.6). Wave AC (Figure 1) is assumed to be weak, and the angles of turn on it are small. It is precisely in this case that expansion (2.4) is valid. In variables ξ and η, weak shock AC is described with the equation:

$$\eta_{AC} = \frac{\xi}{M_\infty^2 - 1}\left(\sqrt{\frac{\xi_\infty}{\xi}} - 1\right)^2. \tag{3.1}$$

From the laws of conservation of momentum and mass and the laws for joining the flow on AB, we obtain:

$$A'' = \frac{2\xi j - 1}{4\xi\tau}\left[\frac{y_{AB}^2}{2h_p} - \frac{\lambda\nu}{2(\lambda_\infty - \lambda)} - A^2(\eta_{AB} - \eta_{AC})\right] - \frac{A'^2}{A} - \frac{1 - \xi j}{\xi}A' + \frac{3j}{4\xi}A, \tag{3.2}$$

$$B'' = \frac{2\xi j - 1}{4\xi}\left[\frac{\eta_{AB}^2 + \tau}{\tau}\frac{y_{AB}^2}{2h_p} - \frac{2\eta_{AB}^2 + \eta_{AC}^2}{\eta_{AB} - \eta_{AC}}A - \frac{2}{2\xi j - 1}B' - \frac{\lambda\nu}{2\tau(\lambda_\infty - \lambda)}\right],$$

$$y_{AC}^2 = \frac{\nu\sqrt{\xi}}{\lambda_\infty - \lambda}, \quad \left(\lambda = \frac{\sqrt{\xi}}{h_p}, \ \tau = \eta_{AB}^2 - \eta_{AC}^2, \ \nu = 2B' - \frac{(\xi A^2)'}{\xi}\eta_{AC}^2\right),$$

where y_{AB} and η_{AB} are functions of ξ, determinable with system (1.1) and (1.5) - (1.7); index ∞ relates to the corresponding leading undisturbed flow parameters. /76

The general system of equations (1.1), (1.5) - (1.7), (3.1) and (3.2) determines total flow, i.e. gives the solution to the problem of joining vortex flow (1.1) with even flow.

Shock wave AB reaches the axis if y = 0 in (1.3), i.e. if either $\Psi = \Psi_0$ (a) or z' = 0 (b). In first case (a), we have $\rho_0 = 0$ for total pressure on the axis, which is impossible. We will consider the second variation, $z' = 0$. For (1.1), this is a singular point through which the single-parameter family of equations $z = \sqrt{1 - h_0} + k(h_0 - h)^2$ passes (h_0 is the value for enthalpy on the axis and k is the parameter). Here, according to (1.2), $v = 0$ on the axis. It follows that the shock wave reaches the axis and approaches it at a straight angle.

Calculations are made from the axis. Given M_∞ and α, we find parameter k, which fixes the integral curve in the family of solutions passing through the antinode point. Further, departing from the singular point according to the analytic solution, we solve the general system of common differential and transcendental equations (1.1), (1.5) - (1.7), and (3.1) - (3.2). At each integration step for the differential equations, the system of transcendental equations (1.5) is solved by iteration [2]. Here a solution from the preceding step is selected as the initial approximation for the iteration process. Calculation continues up to $y = y_{max}$, whose value corresponds to flow lines $\Psi_{max} = \Psi_0 - C^{-1/\alpha}$.

4. The intensity of shock wave AB decreases as y_{AB} increases and falls to zero when $y = y_{max}$. Intensity changes due to solid wall distortion and uneven flow in Ω_1. At values of $\alpha \leq 1$, the unevenness of flow in Ω_1 is insignificant (when $\alpha = 0.1$, the maximum value of $\Delta\vartheta_1/\Delta_\psi$ on the external side of the shock is 0.06, and when $\alpha = 0.01$, $\Delta\vartheta_1/\Delta_\psi = 10^{-4}$) and shock distortion is due basically to wall distortion. In this case leading wave AC is almost a characteristic curve and the Ω_1 zone has significant dimensions. As α increases, the flow in Ω_1 becomes more uneven, AC begins to differ from the characteristic curve, and zone Ω_1 decreases. Here the vorticity in Ω_2 can be explained not only by wall distortion, but also by uneven flow in front of the shock. Note that here the hypotheses on which the solution in Ω_1 are based are met with decreasing accuracy.

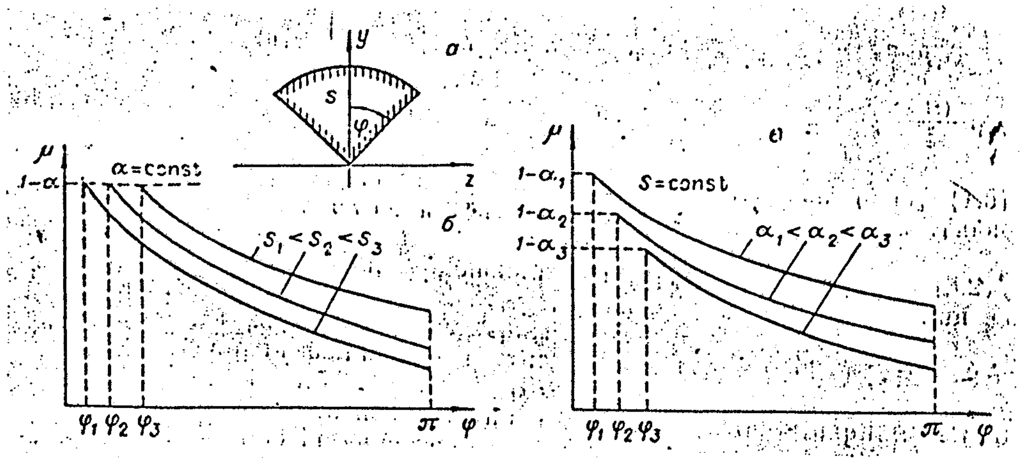

Figure 3

We use the solution obtained to describe the flow in airscoops constructed by an excision along the streamlines of an axisymmetric flow [3, 4]. We will discuss a sector excision with angle 2ϕ (Figure 3 a). The combined loss coefficient for total pressure is determined according to the formula

$$\mu_{\Sigma} = \iint p_0 dS, \tag{4.1}$$

where S is the area of the capturable gas jet.

The average recovery factor for total pressure for this diffusor formula is

$$\mu = \frac{\mu_{\Sigma}}{S} = (1-\alpha)\, C \left(\frac{S}{\varphi}\right)^{\alpha\cdot(1-\alpha)} \tag{4.2}$$

Figure 3 b shows μ as a function of the angle of sector ϕ at different values for S, and Figure 3 c shows μ as a function of index α. The influence of α on the recovery factor increases with ϕ. In Figure 4 the values of ϕ_i are determined with the equation $\phi_i = S_i/y_{max}$, which shows that $y \leq y_{max}$. /77

To evaluate the level of compression for the gas jet entering the airscoop, we determine pressure on AD (see Figure 1). On AD $h = \text{const} = h_i$. Then

$$\frac{p}{p_\infty} = C\left(\frac{h_1}{h_\infty}\right)^{\varkappa/(\varkappa-1)} (\psi_0 - \psi)^\alpha,$$

We obtain the following for total compression

$$\chi_\Sigma = C_1 \mu_\Sigma, \quad C_1 = \left(\frac{h_1}{h_\infty}\right)^{\varkappa/(\varkappa-1)},$$

where μ_x is determined in (4.1).

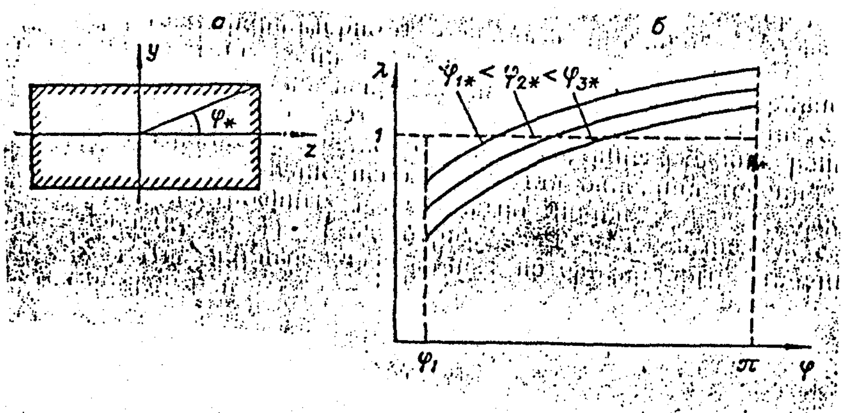

Figure 4

The characteristics of intake diffusors with other excision shapes can be determined in a similar manner. Figure 4 shows a diffusor with a rectangular excision which can be characterized with two parameters: the area of captured jet S and angle ∅, shown on Figure 4 a. Figure 4 b shows the curve for the ratio of diffusor recovery factor (Figure 4 a) to the analogous value /78
(4.2) characterizing the influence of excision shape on aerodynamic characteristics.

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