ICAS PAPER
No. 72 – 37

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NON-EQUILIBRIUM SUPERSONIC FLOWS

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The Eighth Congress of the International Council of the Aeronautical Sciences

INTERNATIONAAL CONGRESCENTRUM RAI–AMSTERDAM, THE NETHERLANDS
AUGUST 28 TO SEPTEMBER 2, 1972

Price: 3. Dfl.

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Abstract

An effective numerical method using two-dimensional characteristic compatibility relations is worked out for the computations of three-dimensional supersonic gas flows with non-equilibrium physico-chemical processes. This method is applied to the numerical analysis of supersonic flows of non-equilibrium dissociating oxygen in non-axisymmetrical nozzles and about blunt-nose direct and inverse cones at angle of attack. Some calculated results are presented as graphs which describe the distributions of various physical parameters on the body surface and inside the flow-field. The non-equilibrium effects are investigated by the comparison with the corresponding data for frozen and equilibrium streams.

1. Introduction

It is well known that various physico-chemical transformations due to strong heating, proceed in supersonic high-temperature gas flows in nozzles or for flight of hypersonic vehicles. These processes involve such phenomena as excitation of vibrational degrees of freedom, molecule decay and atom exchange, excitation of electron levels of molecules and atoms, ionization. Depending on conditions the rate of these processes can be different. In two limiting cases, when the rate is zero or infinite, the frozen or equilibrium physico-chemical transformations take place, respectively.

In general case the rates of reactions are finite and thus non-equilibrium irreversible processes occur in a gas. The degree of non-equilibrium is defined by the ratio of relaxation time to a characteristic time of flow. Not only the velocity, temperature and pressure of free stream, but also the linear size of the body determine the properties of non-equilibrium flows. When the linear size or the pressure increase, the flow approaches the equilibrium regime; when these parameters decrease, the flow approaches the frozen regime.

The relaxation time for different reactions taking place in non-equilibrium streams of multi-component gas mixture may be essentially different. Besides that the rate of an individual reaction may vary rather widely in the flow region. The simultaneous presense of slow and rapid processes complicates the numerical calculation of non-equilibrium gas streams. However the principal difficulty is here connected with the behaviour of relaxation equations which are the equations of stiff type. The coefficient at the highest derivative in these equations tends to zero when the flow approaches the equilibrium state. This fact can cause a numerical instability for integrating the relaxation equations. To avoid this instability it is necessary to use implicit difference schemes or some special techniques.

Two-dimensional and axisymmetrical non-equilibrium supersonic flows of gas have been studied in detail. As to three-dimensional non-equilibrium streams (gas motion in non-axisymmetrical nozzles or flow about a body at an angle of attack), only several works are published on this topic. The transition from numerical solution of plane and axisymmetrical problem to three-dimensional one requires not only more complicate computating algorithms and larger bulk of calculations, but essentially complicates a flow-field structure and increases its non-uniformity; as a result, there appear serious numerical difficulties.

The investigation of three-dimensional non-equilibrium supersonic gas streams, taking into account a sufficiently accurate kinetics of physico-chemical processes, is very important. However reliable physical data involved in kinetics equations are mainly available for simple gases (oxygen, nitrogen) which by this reason are considered more often to study three-dimensional non-equilibrium flows. In the case of the air, several tens reactions between gas components may arise, therefore here it is usually introduced a kinetics model including only some basic reactions (dissociation, exchange processes in atom-molecule collisions, associative ionization).

The papers published on three-dimensional non-equilibrium supersonic gas streams concern, chiefly, the problem of flow about nose part of a blunted body at an angle of attack. It has been considered the air (1), the oxygen (2), the oxygen, nitrogen and air (3,4). The numerical analysis of purely supersonic flows of non-equilibrium oxygen was carried out for non-axisymmetrical nozzles (5,6) and for blunt-nose inverted cones at angle of attack (7). A small portion of shock layer, disposed behind the sonic surface, was also calculated in the work (3). Supersonic region of three-dimensional non-equilibrium air flow about a body of sphere segment shape was computed in the paper (8); however here the full equations of kinetics were taken only in the symmetry plane of flow. The combustion in three-dimensional supersonic streams has been studied in the work (9) where a model exothermal reaction is used.

2. The governing system of equations

The system of partial differential equations for steady flows of inviscid non-heatconducting gas consists of the well-known continuity, momentum and energy equations

$$\nabla \rho \bar{V} = 0,$$
$$\rho (\bar{V} \nabla) \bar{V} + \nabla p = 0, \qquad (1)$$
$$\rho \bar{V} \nabla h - \bar{V} \nabla p = 0,$$

were $\bar{V}$, p, ρ, h - the velocity vector, pressure, density and enthalpy of gas, respectively.

Physico-chemical processes in a gas are assumed to be described by m determinating parameters c_i $(i = 1, 2, \ldots, m)$. The role of such parameters is played by energies of internal degrees of freedom, mass concentrations of components of gas mixture, etc. We choose as two thermodynamic parameters the pressure p and the temperature T. Then the relaxation equation for each process may be taken in such a general form

$$\frac{dc_i}{dt} = F_i(p, T, c_1, \ldots, c_m) \qquad (2)$$
$$i = 1, 2, \ldots, m.$$

The thermal and calorical equations of state will be represented by the expressions

$$\rho = \rho(p, T, c_1, \ldots, c_m), \qquad (3)$$
$$h = h(p, T, c_1, \ldots, c_m). \qquad (4)$$

The actual form of equations (2)-(4) is given by the physical and chemical kinetics. In the general case, when the change of the parameters c_i depends on K processes, the right-hand parts of relaxation equations (2) have the following structure

$$F_i=\sum_{k=1}^{K} \varphi_{ik}(p,T,c_1,\dots,c_m)f_{ik}(p,T,c_1,\dots,c_m). \quad (5)$$

The function φ_{ik} is proportional to the rate of the k-th physico-chemical process. For flows with frozen reactions $\varphi_{ik}=0$, while for flows with equilibrium reactions $\varphi_{ik}\to\infty$ and $f_{ik}\to 0$. In the equilibrium case there appear the relations $c_i=c_i(p,T)$ and thus here only the pressure and the temperature remain as the determining parameters.

The governing system (1)-(4) allows to calculate non-equilibrium gas streams. As known, this system is elliptic at subsonic velocities, while it is hyperbolic at supersonic velocities. It is possible to compute supersonic region starting from the initial data obtained on a space-like surface, i.e. on such a surface where the normal velocity at any point is much than frozen sound velocity a

$$a=\left[\frac{\partial\rho}{\partial p}+\frac{\partial\rho}{\partial T}\left(\frac{\partial h}{\partial T}\right)^{-1}\left(\frac{1}{\rho}-\frac{\partial h}{\partial p}\right)\right]^{-1/2} \quad (6)$$

The boundary condition on the body surface for the system (1)-(4) is the condition of vanishing normal velocity. On the shock assumed as a discontinuity front of zero thickness, the Rankine-Hugoniot relations hold, no vibrational degrees of freedom are excited, and concentrations of all the chemical components are frozen.

3. The numerical method of solution

The numerical method using two-dimensional characteristic compatibility relations was worked out [5,6,10] for three-dimensional non-equilibrium supersonic gas flows.

The original system of equations (1)-(4) is taken in the cylindrical coordinates x, r, ψ connected with the body. The axis x is directed along the body axis. For simplicity, we confine ourselves to smooth bodies with a symmetry plane parallel to uniform free stream; thus $0^\circ\leq\psi\leq\leq 180^\circ$. A flow region is supposed to be bounded along two sides by some surfaces $r=r_b(x,\psi)$ and $r=r_s(x,\psi)$. In the case of external flow about a body, the first surface is the body surface and the second one is the shock wave. The normalized variable $\xi=(r-r_b)/(r_s-r_b)$ is introduced instead of r.

The derivatives with respect to ψ are eliminated from the governing system rewritten in the variables x, ξ, ψ. Odd, $\bar{f}$, and even, $\tilde{f}$, functions in ψ are approximated by trigonometrical polinomials

$$\bar{f}=\sum_{n=1}^{L-1}\sum_{l=1}^{L-1} c_{nl}\bar{f}_l \sin n\psi,$$
$$\tilde{f}=\sum_{n=0}^{L}\sum_{l=0}^{L'} d_{nl}\tilde{f}_l \cos n\psi. \quad (7)$$

Here, we take as interpolation nodes $L+1$ equally spaced meridional semi-planes $\psi=\psi_l=l\pi/L$ $(l=0,1,\dots,L)$, the subscript l denotes the value of a function in the corresponding meridional semi-plane, c_{nl} and d_{nl} are the numerical coefficients.

As a result, the original three-dimensional system is reduced to the approximating system of differential equations in two independent variables x and ξ, but for the values of basic functions in all $L+1$ semi-planes $\psi=\psi_l$.

Now we introduce some designations

$$\lambda=-\xi\left(\frac{\partial r_s}{\partial x}-\frac{\partial r_b}{\partial x}\right)-\frac{\partial r_b}{\partial x},$$

$$\mu=-\frac{1}{r}\left[\xi\left(\frac{\partial r_s}{\partial\psi}-\frac{\partial r_b}{\partial\psi}\right)+\frac{\partial r_b}{\partial x}\right],$$

$$\zeta = \frac{v + \mu w}{u},$$

$$\beta = \sqrt{\frac{u^2 \zeta^2}{a^2} + (1+\mu^2)\left(\frac{u^2}{a^2} - 1\right)},$$

where u, v, w are the velocity components along the directions x, r, ψ, respectively; a is the frozen sound velocity (6).

The approximating system is hyperbolic in a supersonic region, where the quantity β is real. In the each meridional semi-plane of interpolation, this system possesses two families of wave characteristics and one family of analogoues of stream lines, which are describing by the equations

$$\frac{d\xi}{dx} = \frac{1}{r_s - r_b}\left(\lambda + \frac{u^2\zeta \pm a^2\beta}{u^2 - a^2}\right),$$

$$\frac{d\xi}{dx} = \frac{1}{r_s - r_b}\left(\lambda + \zeta\right). \tag{8}$$

The following compatibility relations hold along the wave characteristics

$$d\zeta \pm \frac{\beta}{\rho u^2}dp + \frac{1}{u^2}\Big[\Phi_1 \frac{u a^2(\zeta \pm \beta)}{u^2 - a^2} - \Phi_2 \frac{u^2\zeta \pm a^2\beta}{u^2 - a^2} + \Phi_3 + \mu\Phi_4 - u w \frac{d\mu}{dx}\Big]dx = 0. \tag{9}$$

The compatibility relations along the analogoues of stream lines have such a view

$$\mu\, dv - dw + \frac{1}{u}(\mu\Phi_3 - \Phi_4)dx = 0,$$

$$du + \zeta\, dv + \frac{1}{\rho u}dp + \frac{1}{u}(\Phi_2 + \zeta\Phi_3)dx = 0. \tag{10}$$

In addition, the energy equation from (1) and the equations (4) must be considered along the last lines, namely

$$dT - \left(\frac{1}{\rho} - \frac{\partial h}{\partial p}\right)\left(\frac{\partial h}{\partial T}\right)^{-1}dp + \frac{\Phi_5}{u}dx = 0,$$

$$dC_i + \frac{\Phi_{5+i}}{u}dx = 0. \tag{11}$$

All the compatibility relations taken in each semi-plane of interpolation are interconnected, since the quantities Φ include the derivatives with respect to ψ, which are defined by the approximations (7) in terms of the values of basic functions in all the semi-planes $\psi = \psi_\ell$.

The numerical method using two-dimensional characteristic compatibility relations is based on the finite-difference representation of the differential equations (8)-(11). Here, it is constructed a implicit numerical scheme of the second order of accuracy. The solution is calculated on successive planes $x=$ const at nodal points with fixed values of $\xi =$ const, which are identical for all the interpolation semi-planes $\psi =$ const. The characterictic lines are issued from the nodal point under calculation towards the previous earlier computed plane $x=$ const where the values of functions at the corresponding points of intersection are defined by quadratic interpolation. The finite-difference equations are solved by iterations carried out simultaneously at all the nodal points with identical value of ξ and different values of ψ. The concrete computing algorithms are given in the works (5, 6, 10). A special difference scheme of the second order of accuracy is developed for stable and effective integration of the relaxation equations near the equilibrium. In this scheme, the functions f_{ik} from (5) are not calculated explicitly at the point with equilibrium state, but are represented by two-term expansion in that parameter C_i, which tends to the equilibrium value.

The given numerical scheme has a special construction. The application of trigonometrical approximations, taking into account the behaviour of gas cross motion in three-dimensional flows about smooth bodies, allows to approximate the derivatives using simultaneously all the nodal points in this direction. As a result, sufficiently accurate solution is obtained for small number (five-nine) of interpolation semi-planes. The actual reduction of three-dimensional problem to two-dimensional one makes the scheme really simple. Here it is used a fixed network which may be easily refined in narrow local zones with large transverse gradients, arisen in non-equilibrium flows. In this scheme, it is convenient to integrate the relaxation equations hold along stream line. The implicit type and the second order of accuracy ensure numerical stability and economical realization of the scheme.

4. The discussion of numerical results

The developed method has been applied to the numerical analysis of three-dimensional supersonic streams of non-equilibrium dissociating oxygen in non-axisymmetrical nozzles and about blunted cones at angle of attack.

Concerning the kinetics it is supposed the equilibrium excitation of internal degrees of freedom, the absence of electrone level excitation and of ionization. In such a case, there exists the single non-equilibrium parameter c – the dissociation degree, that is the mass concentration of atomic oxygen. The kinetics equations are assumed to be the same as those in the work [11].

The thermal and calorical equations of state (3) and (4) for a diatomic gas are taken as follows

$$\rho = \frac{p}{T}\,(1+c)\,,$$

$$h = \frac{7+3c}{2}\,T + \Theta_D c + (1-c)\theta_v \frac{\exp(-\theta_v/T)}{1-\exp(-\theta_v/T)}.$$

The function φ and f from the expression (5) are

$$\varphi = \frac{\Lambda \rho}{T^s(1+c)}\left[2c + \frac{k_{R2}}{k_{R1}}\,(1-c)\right],$$

$$f = \chi\,(1-c^2)\sqrt{T}\left[1-\exp\left(-\frac{\theta_v}{T}\right)\right] \times$$

$$\times \exp\left(-\frac{\theta_D}{T}\right) - \frac{\rho c^2}{T}\,.$$

Here, θ_D, θ_v, χ, Λ, s are certain dimensionless physical parameters, k_{R1} and k_{R2} are the constants of recombination rate for triple collision; their values are presented in the work [11].

The basic functions in the above equations and everywhere below will be considered as dimensionless, assuming as reference quantities the certain length, the free stream density ρ_∞ and velocity V_∞, the gas constant of oxygen R.

At first, we shall analyse a non-equilibrium flow in non-axisymmetrical nozzle being a tube of elliptic cross-section (with semi-axes ratio $a/b = 1.5$, $a = 0.5$ m) with a profiled inner body. The contours of the nozzle in two symmetry planes $\psi = 0^\circ$ and $\psi = 90^\circ$ are shown in Fig.1. At the nozzle entrance ($x = 0$) the cross-section of the inner body is also a similar ellipse with focal semi- length equal to 0.362 m (this quantity is taken as the reference length).

We shall discuss some numerical results for the case when the oxygen stream at nozzle entrance has Mach number $M_\infty = 1.2$, temperature $T_\infty = 5{,}000^\circ$K and pressure $p_\infty =$ 1 atm. Here we present the distributions of physical parameters along the outer tube of nozzle for $\psi = 0^\circ$ and $\psi = 90^\circ$. All the non-equilibrium data will be plotted by solid lines. It is interesting to compare the non-equilibrium flow with the equilibrium and frozen flows in nozzle for the same entrance values of velocity, temperature and pressure. The results for two these limiting cases will be drawn by dashed-dotted and dashed lines, respectively.

The change of dissociation degree C is given in Fig.2. Naturally, this quantity in frozen flow is constant. Since the temperature drops in accelerating non-equilibrium stream in nozzle, the recombination of oxygen atoms proceeds and therefore the dissociation degree decreases along the nozzle. The non-equilibrium curves of dissociation degree are initially close to equilibrium dependences. Subsequently the flow deflects from equilibrium state and rather rapidly becomes frozen owing to intensive expansion. Then the dissociation degree remains practically constant, but different along diffeferent generators of nozzle.

The behaviour of temperature is considered in Fig.3. The recombination accompanied by a heat release causes a temperature rise in comparison with the case of frozen reactions. Non-equilibrium curves essentially differ from equilibrium ones and pass between equilibrium and frozen dependences corresponding to two limiting reaction rates.

The variation of Mach number is illustrated in Fig.4. For frozen reaction a strong drop of temperature diminishes sound velocities and increases Mach numbers. In non-equilibrium (as well as in frozen) and in equilibrium streams, Mach number is defined through frozen and equilibrium sound velocity, respectively. As a result, the total difference between Mach number distributions in two these cases reduces, though the Mach number of equilibrium free-stream at the same velocity V_∞ rises to $M_\infty = 1.316$.

Now we shall study how the non-equilibrium dissociation affects a flow-field and aerodynamic properties of blunted cones at an angle of attack α. We shall consider, mainly, inverted elliptic cones with semi-apex angles $\omega < 0$ and also direct cones ($\omega > 0$). At first we present some numerical results for bodies having an ellipsoid bluntness with the semi-axes ratio $b/a = 1.5$ and the axis $b = 1$ m set in the symmetry plane of flow. This size b is taken as the reference length. We direct the axis x along the body axis from its front point and assume that $\psi = 0^\circ$ relates to the windward side and $\psi = 180^\circ$ to the leeward side. The free stream of non-dissociated oxygen has the following parameters: $M_\infty = 10$, $\alpha = 10^\circ$, $T_\infty = 300^\circ K$, $p_\infty = 0.001$ atm. We have computed the supersonic flow region starting from initial data at $x = 0.5$, obtained by numerical methods [2] and [12] [also see [13]] for the flow about nose part of the body.

The shape of shock wave in the symmetry plane for the inverted cone $\omega = -30^\circ$ is shown in Fig.5. The solid line relates to non-equilibrium dissociating oxygen and the dashed line to frozen (diatomic perfect) gas. The dissociation of oxygen molecules behind the shock wave, going with heat absorption, causes significant drop of temperature and rise of density in shock layer. This effect changes the geometry of flow-field pattern. The shock wave detachment in real gas is shortened, being in non-equilibrium case somewhat larger than in equilibrium one. The diminution of sound velocity, due to dissociation, decreases the total size of subsonic zone in shock layer. The stagnation point on the body removes some more towards the position of maximum body cross-section.

The pressure distributions along surface of blunted bodies (inverted cones, a direct cone $\omega = 10^\circ$ and a cylinder $\omega = 0^\circ$) are presented in Fig.6, where the data are plotted for the windward generator $\psi = 0^\circ$ (solid line) and for the leeward generator $\psi = 180^\circ$ (dashed line). This curves have two portions related to the ellipsoid bluntness and to conical surface. The flow behaves itself differently along the windward and leeward sides of inverted cones. The cross-flow and retardation of gas sharply increase the pressure on the leeward side near the aft body point. Here a secondary shock wave and a local subsonic zone arise, thus it is not possible to carry out the calculations by the method of characteristics up to the aft point. For comparison, the appropriate data in a perfect diatomic gas for an inverted cone $\omega=-30^{\circ}$ are indicated by crosses in this graph. As seen, the non-equilibrium dissociation a little influences the pressure distribution.

The similar graph for temperature distribution is presented in Fig.7. The comparison with results for frozen flow about an inverted cone $\omega=-30^{\circ}$ (crosses) demonstrates how the relaxation process decreases the gas temperature.

Figure 8 gives the change of Mach number along several generators on an inverted cone $\omega=-30^{\circ}$ in non-equilibrium (solid lines) and frozen (dashed lines) streams. The dissociation process deminishes Mach numbers on the body, but it still more diminishes total velocity (approximately by 25-30 per cent on the conical portion of body). The relaxation effect for Mach number is weakened because of a reduction of sound velocity. It is interesting that Mach number varies non-monotonically near the aft point; in fact, the values of M for $\psi = 180^{\circ}$ are less than for $\psi = 90^{\circ}$ or $\psi = 135^{\circ}$.

The last circumstance is due to a behaviour of peripheral velocity w characterizing a three-dimensional feature of flow. The body distributions of function w on versus ψ at various fixed distances x is shown in Fig.9. The peripheral velocity in non-equilibrium case (solid lines) is less than in frozen one (dashed lines). Approaching the aft body point, the peripheral velocity rapidly rises and the position of its maximum removes towards the leeward side.

Now we shall analyse a change of some physical functions across shock layer on an inverted cone $\omega=-30^{\circ}$. Appropriate graphs versus the normalized variable ξ ($\xi=0$ relates to the body surface, $\xi = 1$ to the shock wave) are plotted in Fig. 10-14 at a number of x in a certain semi-plane $\psi =$ const.

The dissociation degree distribution across shock layer ($\psi = 180^{\circ}$) is given in Fig.10 not only in supersonic region, but also along the axis x ($r=0$) and the limiting characteristic bounding the minimal domain of influence (dashed-dotted line). Transverse gradients of dissociation degree within the shock layer are fairly large, while its longitudinal gradients on the body surface are very small.

The temperature profiles (Fig.11, $\psi= 0^{\circ}$) are non-monotonic, reaching a maximum between body and shock wave. The non-equilibrium dissociation most intensively decreases the body surface temperature.

The density (Fig.12, $\psi = 180^{\circ}$) rises from body to shock wave. The density profiles become very steep at large distances x and consequently the most part of gas is concentrated near shock wave. This graph also illustrates how a shock layer becomes more dense owing to dissociation. It should be noted that pressure also rises from body to shock wave.

The behaviour of peripheral velocity at $\psi= 90^{\circ}$ is shown in Fig.13. This function weakly varies near shock wave, but it rapidly increases near body surface at large x . The radial velocity (Fig.14, $\psi= 0^{\circ}$) is positive at $\xi=0$ and negative at $\xi=1$. Hence, the gas moves to body surface in one part of shock layer and to shock wave in other part. The axial velocity somewhat rises from body to shock wave, while the Mach number changes non-monotonically, having a minimum inside shock layer.

The non-symmetry of stream at angle of attack $\alpha=10^{\circ}$ appreciably influences a flow-field. Concerning an effect produced by angle of attack, it is possible to judge by Fig.15 where the pressure distributions are plotted along the windward (solid lines) and the leeward (dashed lines) generators of a inverted cone $\omega=-20^{\circ}$ in non-equilibrium dissociating oxygen stream at various angles of attack $\alpha = 0^{\circ}$, 5°, and 10°. When angle of attack increases, a stiff rise of pressure (and also temperature) occurs on the leeward side near the aft body point.

Now let us consider aerodynamic coefficients for total forces acting upon a body. We shall present some results for several inverted cones with spherical bluntness of radius $b = 1\,m$ in a non-equilibrium dissociating oxygen stream with the following parameters: $M_\infty = 10$, $p_\infty = 0.001$ atm, $T_\infty = 288^\circ K$. The graphs will be given for angles of attack $\alpha = 10^\circ$ (solid lines) and $\alpha = 15^\circ$ (dashed lines). The appropriate data for a diatomic perfect gas will be indicated by circles and triangles. The aerodynamic coefficients are referred to the free-stream dynamic head and the maximal cross-section area of body.

The coefficient of normal force C_n and the coefficient of longitudinal moment C_m (with respect to the axis passing through the front body point) are plotted in Fig.16 as functions of body length x. The similar graph for the ratio of normal and tangential force coefficients, $K = C_n/C_t$ is given in Fig.17. Here additionally, some curves for the position of centre of pressure, $x_c = C_m / C_n$ are depicted for non-equilibrium stream at $\alpha = 10^\circ$. It should be remarked that x_c - curves for $\alpha = 15^\circ$ and for perfect gas don't practically differ from the presented curves for $\alpha = 10^\circ$. An investigation proves that for considered inverted cones, the coefficients C_n and C_m are linear functions of angle of attack up to fairly large values of α ; the dependence $K = K(\alpha)$ is also close to linear. A non-equilibrium dissociation very slightly affects the aerodynamic coefficients, since this relaxation process weakly influences the body pressure distribution.

The numerical analysis carried out has allowed to study non-equilibrium dissociation effects for three-dimensional supersonic flow-fields. It has been found that a finite rate of process results in both quantitive, and qualitive changes of flow properties.

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FIGURES

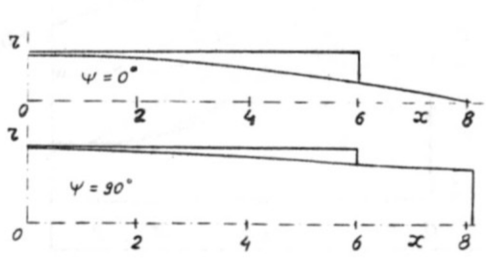

Fig. 1.

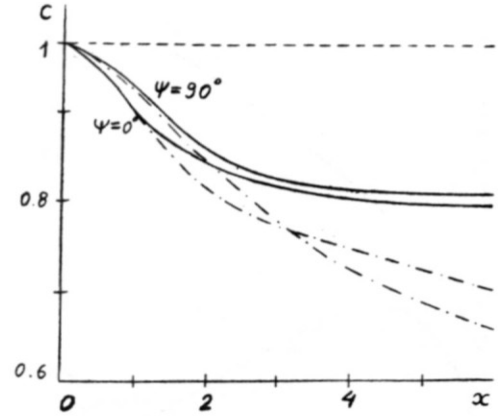

Fig. 2.

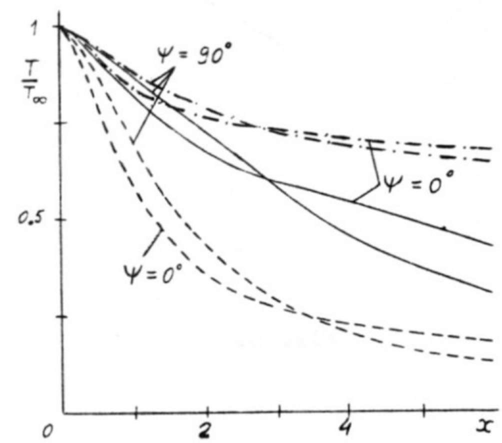

Fig. 3.

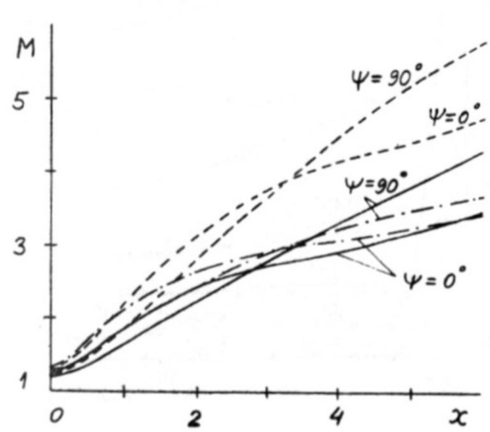

Fig. 4.

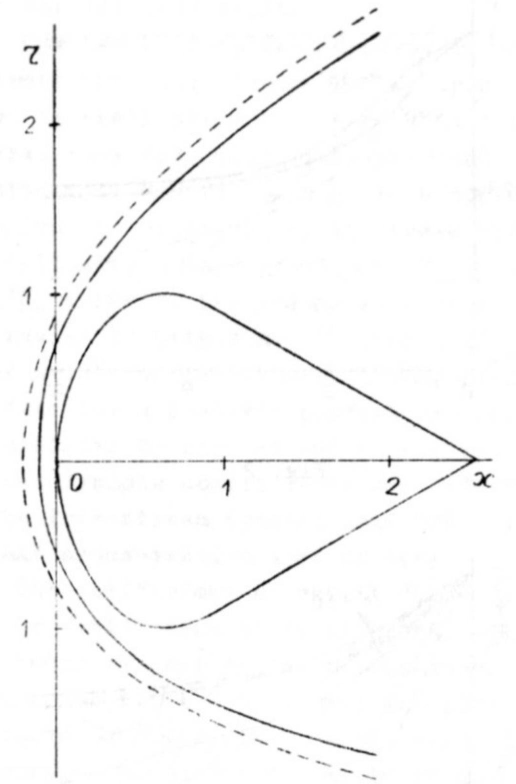

Fig. 5.

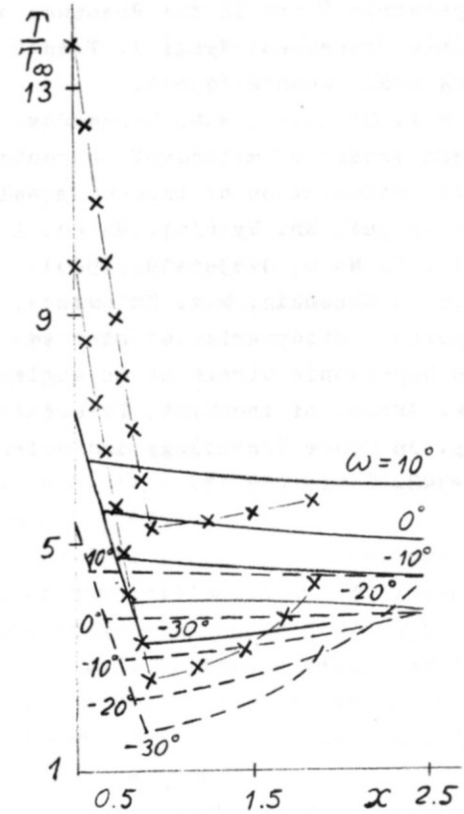

Fig. 7.

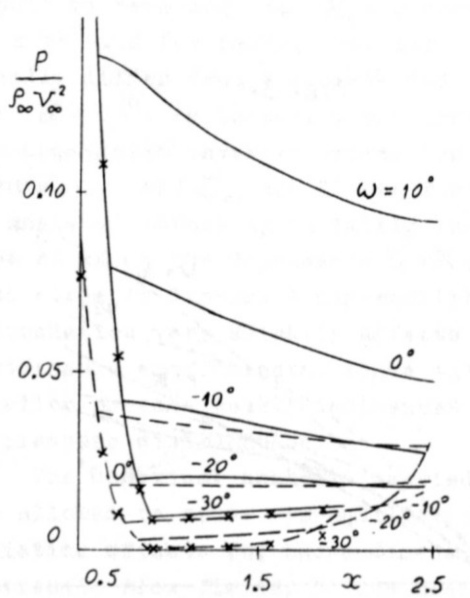

Fig. 6.

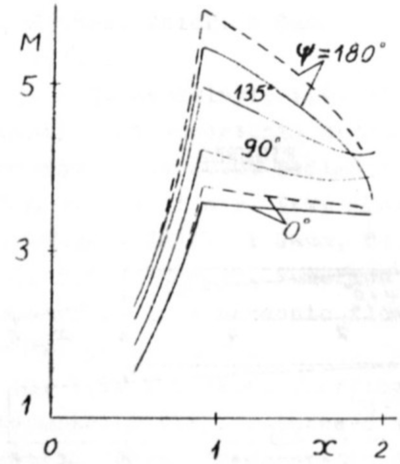

Fig. 8.

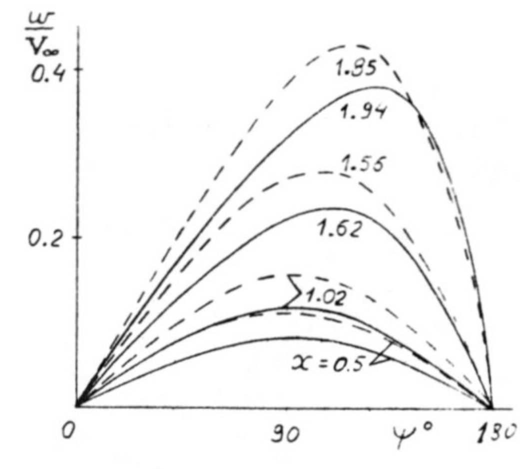

Fig. 9.

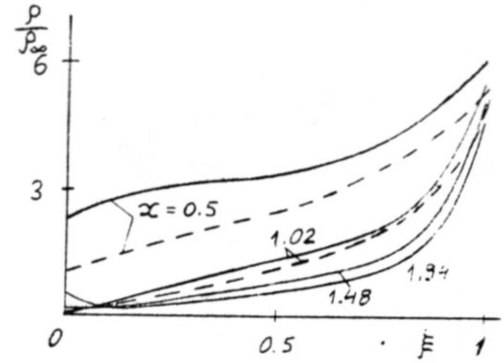

Fig. 12.

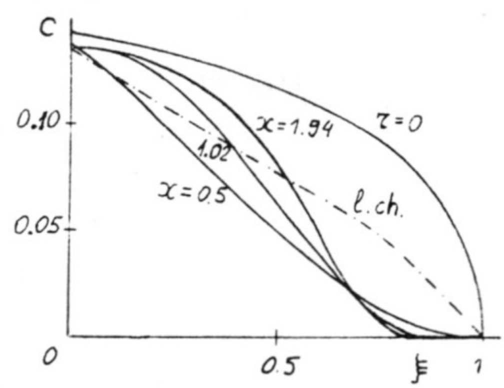

Fig. 10.

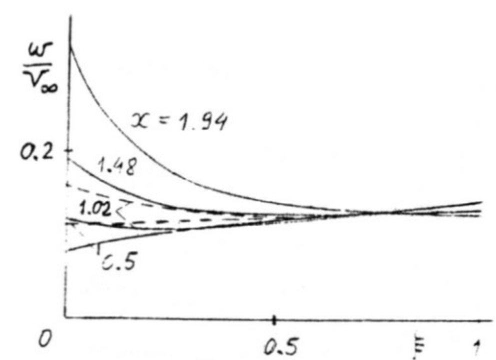

Fig. 13.

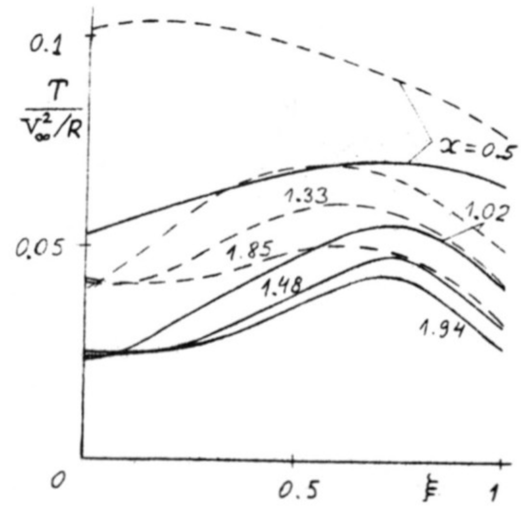

Fig. 11.

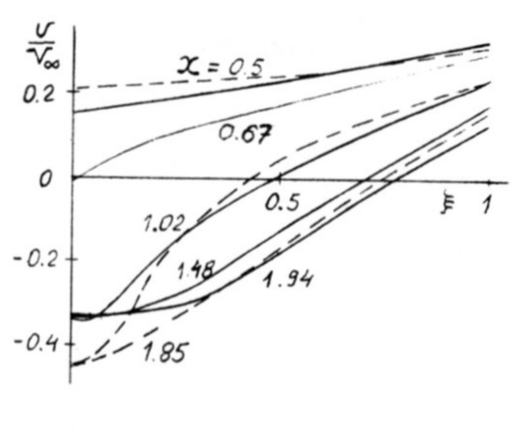

Fig. 14.

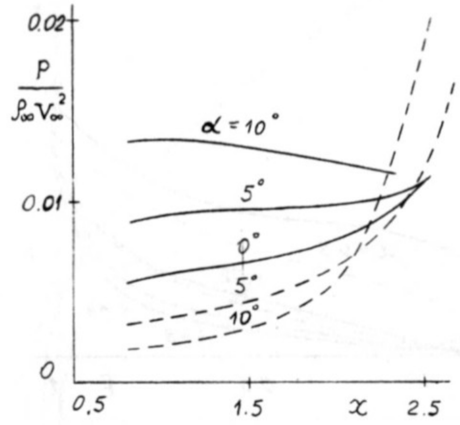

Fig. 15.

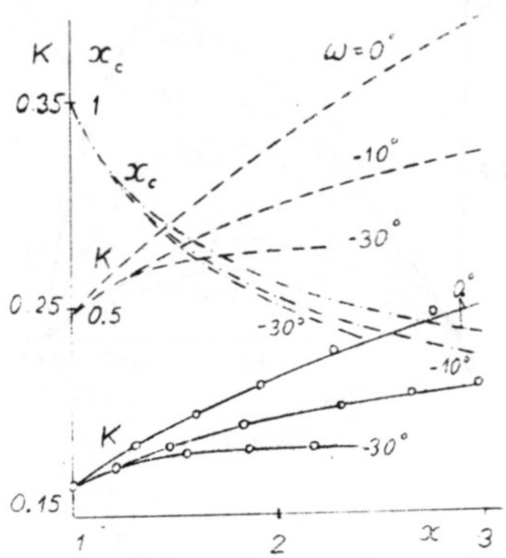

Fig. 17.

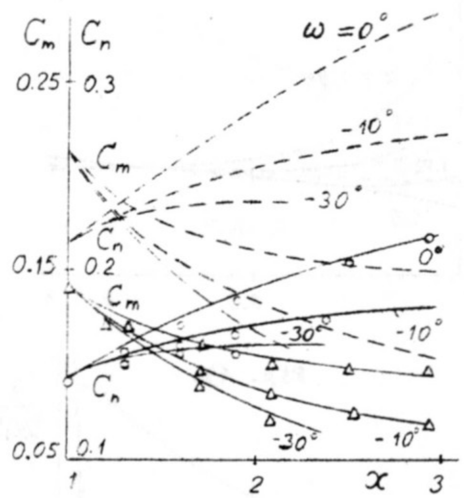

Fig. 16.