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AERODYNAMIC HEATING OF THE LEE SIDE OF A BODY AT SUPERSONIC SPEEDS

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А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*<u>ye</u> initially, after vowels, and after ъ, ь; <u>e</u> elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

GREEK ALPHABET

Alpha	Α	α α		Nu	Ν	ν
Beta	Β	β		Xi	Ξ	ξ
Gamma	Γ	γ		Omicron	Ο	ο
Delta	Δ	δ		Pi	Π	π
Epsilon	Ε	ε ε		Rho	Ρ	ρ ρ
Zeta	Ζ	ζ		Sigma	Σ	σ ς
Eta	Η	η		Tau	Τ	τ
Theta	Θ	θ ϑ		Upsilon	Τ	υ
Iota	Ι	ι		Phi	Φ	φ φ ϕ
Kappa	Κ	ϰ κ ϰ		Chi	Χ	χ
Lambda	Λ	λ		Psi	Ψ	ψ
Mu	Μ	μ		Omega	Ω	ω

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}

---

rot	curl
lg	log

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MT/ST-75-292.

Aerodynamic ~~AEYRODINAMICHESKOYE~~ HEATING OF THE LEE SIDE OF a BODY AT SUPERSONIC SPEEDS.

G.I. Maykapar

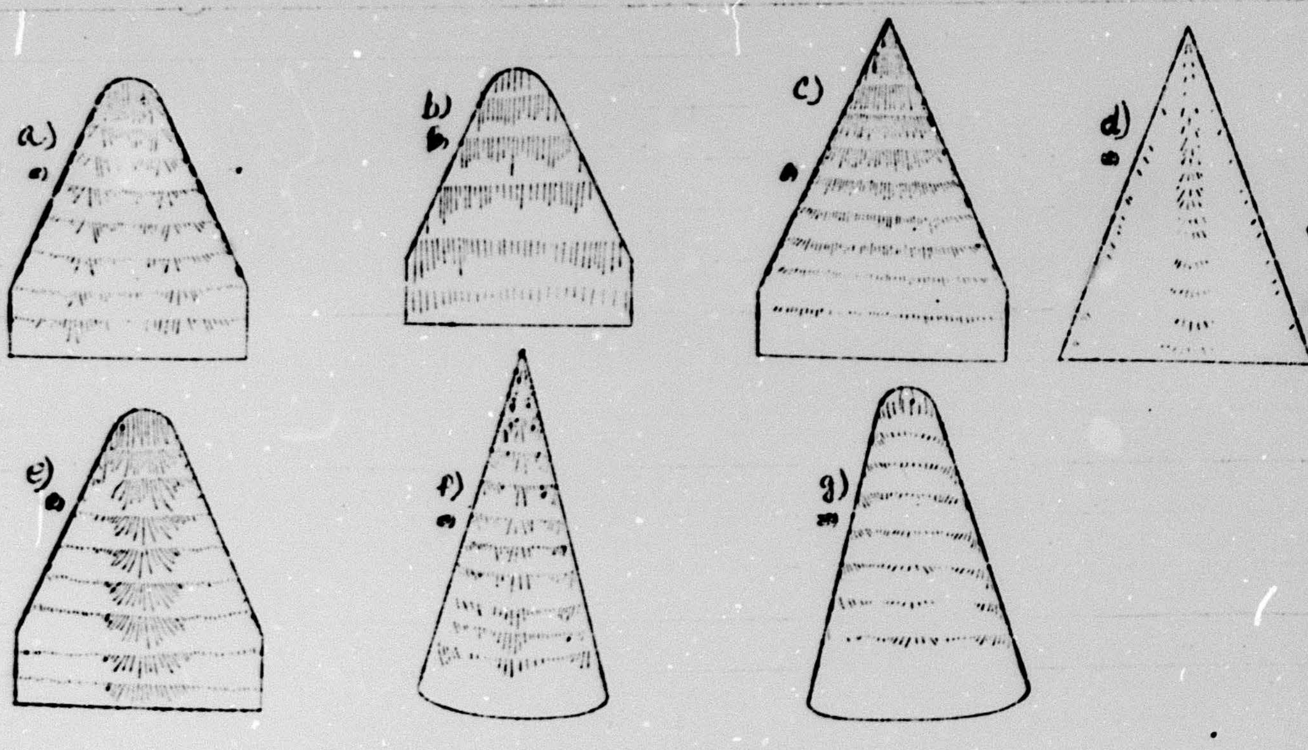
It is shown that the maximum values of heat flux to the flat/plane side of the blunted semicone, directed along flow, are correlated by the parameter of "viscous interaction" $M^3/\sqrt{Re}$. Is presented the hypothesis that the reason for ~~breakaway~~ separation, appearance of "peaks" of heat flux are ~~the swallowed~~ internal shocks waves.

In the experimental studies of V. Ya. Borovoy, R. Z. Davlet-Kil'deyev, M. V. Ryzhkova [1], of Whitehead and Bertram [2], [3], etc. was detected the essential feature of heat transfer to the lee side of body during the detached flow of supersonic flow - the narrow ranges of the heat flux, considerably exceeding heat flux to the surrounding surface (the "peaks" of heat flux). The appearance and the ~~value~~ quantity of peaks depend on numbers M and Re, form, and the angle of attack of body. Peaks appear in the ~~ranges~~ regions of the connection of separated flow where [are] great the stresses of surface friction; therefore the ~~ranges~~ [regions] of connection can be detected from the spectra, obtained with the aid of ~~"[illegible]~~ ["blurring"] which by the flow of the points of color/~~paint~~. Despite the fact that is published a ~~series~~ [number] of the results of the investigations of heat transfer to the bodies of various forms - ~~[illegible]~~ [sharp] and blunt-nosed cones and to semicones, plates, ~~to~~ wedges, ~~to~~ elliptical cylinders, mainly in connection with the absence of the information about the general/~~total~~ structure of flows and methods of calculation, some results [are] difficult to explain and to confidently indicate the means for the elimination of the "peaks" of heat flux. The purpose of article is the explanation of some of the results of experiments.

Fig. 1 gives the spectra of the washed away points of color/~~paint~~ for semicones and triangular plate [1], ~~from~~ [with] analysis of ~~which~~ [whom] we will [begin]. A decrease in Reynolds number both because of the decrease in the pressure and decreases in the ~~significant~~ [characteristic] dimension, for example, a radius of the blunting of semicone, always led to a decrease in the ~~value~~ [quantity] of "peaks". With numbers $M_{\infty} \geq 5$-6, $Re_{\infty} \sim 10^4$, $Re_{\infty}/M^2 \leq 3$ (L

- the length of model) the ~~sign/criteria~~ indication of ~~breakaway~~ separation and "peaks" disappear (see Fig. 1b). There are no ~~sign/criteria~~ indications of ~~breakaway~~ separation near the point of triangular plate [4], obviously, in connection with the fact that entire shock layer is "viscous" and in it there is no pressure gradient, necessary for a breakaway. Since breakaway belongs to the number of phenomena of the interaction of ~~"inviscid"~~ "nonviscous" and "viscous" layers, it was possible to assume that and for it the role of the characteristic parameter will be play(ed by) the known parameter $\bar{\chi}$ ~~$Re^{-1/2}$~~. By scarce experimental points this assumption was confirmed (Fig. 2), ~~In [illegible] to~~ despite an inaccuracy in the determination of "peaks" and ~~to~~ the fact that the results were obtained in different wind tunnels. ~~That~~ The fact that the peaks of heat flux ~~are~~ are not on the flat/plane side of acute/sharp semicone (see Fig. 1c), and also on the convex side of ~~acute/~~sharp semicone $\theta_k=15°$ with ~~forming~~ generatrix directed along flow [1], it is explained, obviously, by the fact that is small the "effective" angle of attack and (there is no) breakaway ~~[illegible]~~. On the flat/plane side of ~~acute/acute polukonusa~~ sharp semicone (see Fig. 1c) are visible only sign/criteria (indications) of local separation in edges.

Fig. 1. Maximum flow lines a) the flat/plane side of the blunted semicone is directed along flow, $\theta_K = 24°.3$, $\alpha = 0$, $M_\infty = 5$, $Re_{L,\infty} = 1.1 \cdot 10^6$, $Re_{L,\infty} M_\infty^{-6} = 70$; b) the flat/plane side of the blunted semicone, $\theta_K = 24°.3$, $\alpha = 0$, $M_\infty = 11.3$, $Re_{L,\infty} = 1.2 \cdot 10^6$, $Re_{L,\infty} M_\infty^{-6} = 0.006$; c) the flat/plane side of sharp semicone, $\theta_K = 24°.3$, $M_\infty = 5$, $\alpha = 0$, $Re_{L,\infty} = 1.1 \cdot 10^6$, $Re_{L,\infty} M_\infty^{-6} = 70$; d) triangular plate, $\theta_K = 18°50'$, $\alpha = 15°$, $M_\infty = 5$, $Re_{L,\infty} = 1.3 \cdot 10^6$; e) the flat/plane side of the blunted semicone, $\theta_K = 24°.3$, $\alpha = 25°$, $M_\infty = 5$, $Re_{L,\infty} = 1.1 \cdot 10^6$; f) the convex side of sharp semicone, $\theta_K = 15°$, $\alpha = 30°$, $M_\infty = 5$, $Re_{L,\infty} = 10^6$; g) the convex side of the blunted semicone, $\theta_K = 15°$, $\alpha = 25°$, $M_\infty = 5$, $Re_{L,\infty} = 10^6$.



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On circular cones the breakaway ensues at angles of attack $\alpha \approx \theta_k$, the "effective" angles of attack of semicones $\theta_k = 24°.3$ * with the flat/plane side, directed along flow, and $\theta_k = 15°$ with ~~forming~~ generatrix, directed along flow, less than the angles (of) "equivalent" along the space of cones (θ_k = 17°.7 and 10°.7 respectively). At ~~high~~ large angles of attack on the flat/plane (see Fig. 1e) and convex (see Fig. 1f) side of semicone the spectra of maximum flow lines and the peaks of heat flux are analogous to those observed in triangular plates [1] - [3] (see Fig. 1d).

It is considerably ~~with~~ more difficult to explain the appearance of two ~~counterstrikes~~ peaks of heat flux on the flat/plane side of the blunt-ended semicone $\alpha = 0$, to ~~α=0, on~~ which correspond two regions ~~ranges~~ of the connection of flow, which go from the points of the coupling of spherical segment with cone (see Fig. 1A), and the disappearance of these peaks ~~with~~ when the leeward convex side $\alpha = 25°$ ~~α=25°~~ (see Fig. 1g). In the latter case the peak of

*[24° 3'] ? or [24.3°] ?

lessvalue, than in the case of sharp semicone, appears only in the rear end of the model, but the feature in heat-flow distributions, connected with pointed coupling of segment with cone, are also noticed [1]. There is no convincing explanation of the reason for the appearance of two peaks of heat flux, which go from the points of the coupling of circular arc and straight generatrix, the rounding of the point of triangular plate [3] and of the disappearance of [illegible] playout the formula of [illegible] [3] and of the heat [illegible] edge of plate [4]. In order to [illegible] explanation to these facts, let us examine the flow about the [illegible] of delta wing. We will be restricted to [illegible], and on [illegible] flow [illegible] the simple waves, which go from [illegible]. [illegible] wave number [illegible] is equal [illegible]. With the small [illegible] flow pattern is [illegible] (Fig. 8), then [illegible] continuous compression in [illegible] $\leq$ [illegible] $\leq$ [illegible]

[illegible] if $\varepsilon > \omega_1$, then is possible only flow with the internal ~~jump of [illegible]~~ shock wave. In the case of flow with internal ~~jump~~ shock is possible both flow with the full rotation of flow before the direction of the axis of plate in ~~jump~~ shock and the flow with the lessslope angle of ~~jump~~ shock β, than in the preceding case, and by the ~~supplementary~~ additional continuous rotation of flow in ~~[illegible] after jump~~ region behind shock. The results of the calculations for the case of full rotation in ~~jump~~ shock are given in Fig. 4-6. The angle of internal ~~jump~~ shock ω_1 very is little affected with a change in angle Λ. [illegible] with angles Λ the pressure ~~after jump p_2~~ behind shock p_2 [illegible] ratio [illegible] with an increase in the angle of attack α.

***********EDITOR: PLEASE CHECK FOR ALL CYRILLIC OR UNCLEAR ITEMS ON THE TABLE (FIGURE) WHICH MAY HAVE BEEN LEFT OUT***********

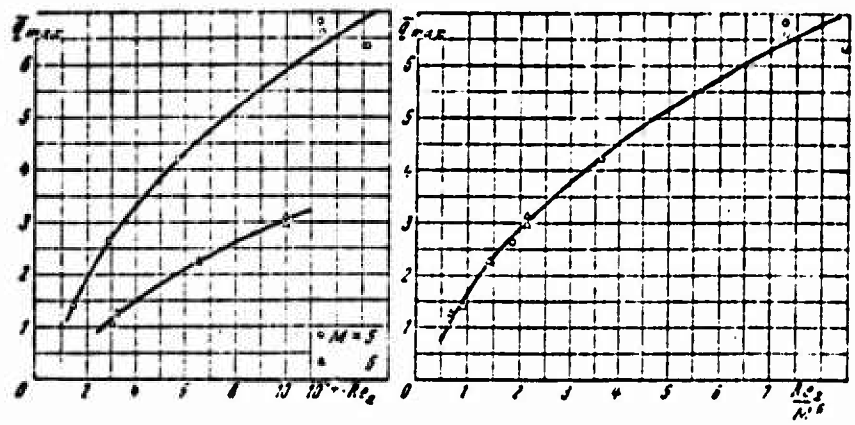

Fig. 4.

Internal shocks were predicted theoretically and obtained in numerical calculations [5]. The measurements showed that their intensity first rises, and then it decreases with removal from the surface of plate.

One of the last works, in which the presence of internal shocks was established by the measurements of the total pressure, is [6]. For this investigation the characteristically low value of parameter $Re_{L,\infty} M_{\infty}^{-6} = 0.3 - 0.4$, corresponding to the regime of "powerful" interaction. Flow separation appeared during angle of attack $\alpha = 90°$ simultaneously with the "suspended" discontinuity.

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[illegible] does not [illegible] plate. Boundary "[illegible]" [illegible] of plate, in consequence of which increases the acceleration/dispersal of gas in simple wave after edge.

*************EDITOR: PLEASE CHECK FOR ALL CYRILLIC OR UNCLEAR ITEMS ON THE TABLE (FIGURE) WHICH MAY HAVE BEEN LEFT OUT************

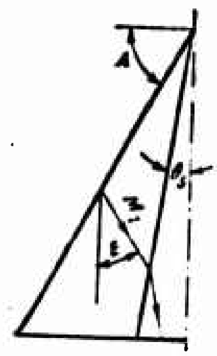


Fig. 3.

Fig. 4. Key: (1) Extreme value α.

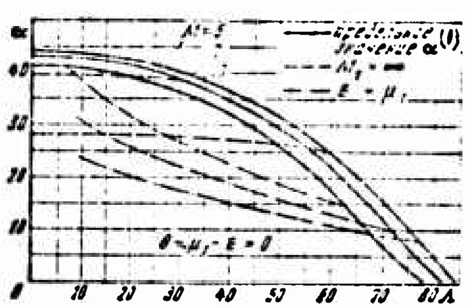
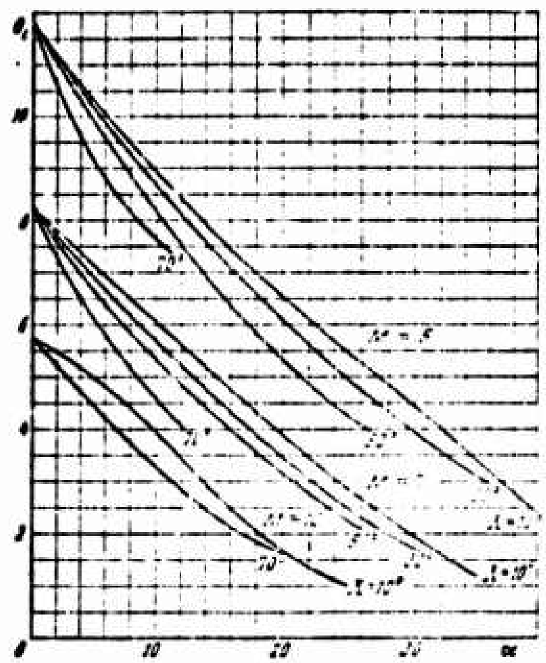


Fig. 5.



In the [illegible] studies of triangular plates [1] - [4] parameter $Re_{L\infty} M_\infty^{-6}$ [illegible] of order [illegible] (region of "weak" interaction), the thickness of "viscous" layer - the order of the thickness [illegible] layer [illegible] [3], and [illegible] less than in investigation [4].

[illegible]

[illegible] with an increase in the angle of attack [illegible]

[illegible] [1] - [4].

[illegible]

[illegible]

[illegible] of

[illegible]

distance between internal shocks and boundary layer thickness differently change with distance from critical point of body, by the interaction of shocks and boundary layer it is possible to explain a change in the configuration of detached flow along the length of body and appearance instead of one peak of heat flux of the two (Fig. 7). With an increase in the angle of attack the angle between internal shocks increases (see Fig. 5), in consequence of which two peaks can pass [illegible].

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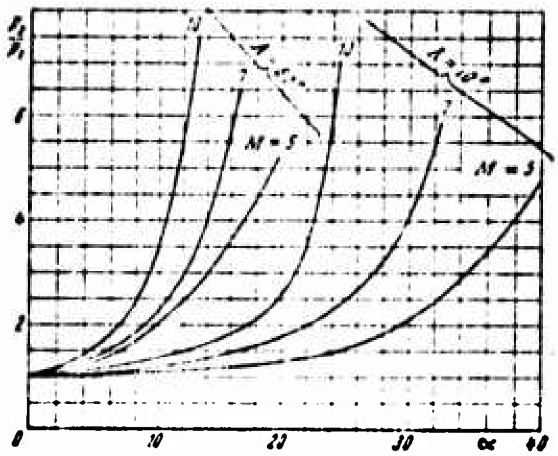
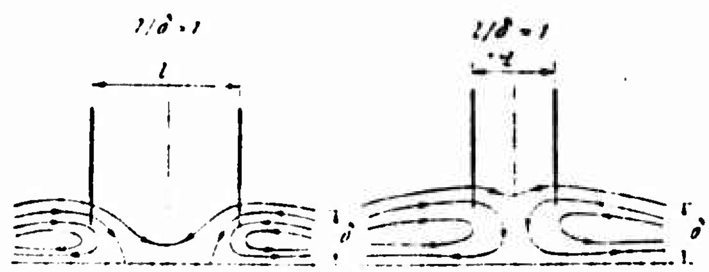


Fig. [illegible]



[illegible]

[illegible] in the angle of attack, sweep angle Λ and number M_∞ the intensity of internal [illegible] the calculation, which must lead to earlier [illegible]. A decrease in angle Λ in the beginning of plate [illegible] p_2/p_1, and also, therefore, the values of the [illegible] of heat flux. [illegible] angles of attack of plate the flow [illegible] similar to [illegible] flow, "internal" or "[illegible]" shock waves are converted into "the closing"; however, [illegible] flow the [illegible] of heat flux on walls is retained to [illegible] (ω = [illegible] 40°), although the absolute value of heat flux to the lee [illegible] as a result of a decrease in density [1]. Flow [illegible] of heat flux on the flat plane [illegible] (see Fig. 13), obviously, are connected with [illegible] stratification of [illegible], [illegible] with a pressure [illegible] after [illegible] flutting.

[illegible] of wedge

a[illegible] leads to an increase in the peaks of heat flux [1].

Page 11[illegible].

[illegible] calculations show that the discontinuity ~~interruption~~ of curvature with the coupling of spherical segment with the surface of [illegible] can lead to the appearance of "suspended" shock waves [illegible] in the case [illegible].

[illegible] relative value [illegible] appearance of [illegible] boundary layer and [illegible] boundary layer.

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