FTD-MT- 63-247

TRANSLATION

INVESTIGATION OF THE INFLUENCE OF RAREFACTION OF SUPERSONIC FLOW ON READINGS OF PROBES OF TOTAL PRESSURE

By

S. I. Kosterin, N. I. Yushchenkova, N. T. Belova, and B. D. Kamayev

FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

WRIGHT-PATTERSON AIR FORCE BASE

OHIO

FOREWORD

This document is a machine translation of Russian text which has been processed by the AN/GSQ-16(XW-2) Machine Translator, owned and operated by the United States Air Force. The machine output has been fully post-edited. Ambiguity of meaning, words missing from the machine's dictionary, and words out of the context of meaning have been corrected. The sentence word order has been rearranged for readability due to the fact that Russian sentence structure does not follow the English subject-verb-predicate sentence structure. The fact of translation does not guarantee editorial accuracy, nor does it indicate USAF approval or disapproval of the material translated.

FTD-MT-63-247

EDITED MACHINE TRANSLATION

INVESTIGATION OF THE INFLUENCE OF RAREFACTION OF SUPERSONIC FLOW ON READINGS OF PROBES OF TOTAL PRESSURE

BY: S. I. Kosterin, N. I. Yushchenkova, N. T. Belova, and B. D. Kamayev

English Pages: 15

SOURCE: Inzhenerno-Fizicheskiy Zhurnal, Vol. 5, Nr. 12, 1962, pp 16-22

S/170/062/005/012

THIS TRANSLATION IS A RENDITION OF THE ORIGINAL FOREIGN TEXT WITHOUT ANY ANALYTICAL OR EDITORIAL COMMENT. STATEMENTS OR THEORIES ADVOCATED OR IMPLIED ARE THOSE OF THE SOURCE AND DO NOT NECESSARILY REFLECT THE POSITION OR OPINION OF THE FOREIGN TECHNOLOGY DIVISION.	PREPARED BY: TRANSLATION DIVISION FOREIGN TECHNOLOGY DIVISION WP-AFB, OHIO.

Tape No. MT-63-247
Engineering Physics Journal, Vol. 5, No. 12, 1962
Pages 16-22

INVESTIGATION OF THE INFLUENCE OF RAREFACTION OF SUPERSONIC FLOW ON READINGS OF PROBES OF TOTAL PRESSURE

S. I. Kosterin, N. I. Yushchenkova, N. T. Belova, and

B. D. Kamayev

4

Results are presented of investigation of the influence of rarefaction of supersonic flow on the magnitude of total pressure, measured by a probe of total pressure with a thin wall and a small exterior angle of slant, ~~for the transi-~~ tional region of the flow regime in the range of change of criteria $0.2 \leqslant M/\sqrt{Re_d} \leqslant 2.00$ and $4.3 \leqslant M \leqslant 6.5$.

It is possible to conduct experimental investigation of flow of rarefied gases at supersonic speeds using for measurement of main gas-dynamic parameters (total pressure P_0', number M and static pressure P_{st} in the flow) probes of total pressure (Pitot tubes), which are widely applied in investigations of supersonic gas flows in the regime of a continuum. However, when the measuring probe of total pressure is used for investigation of sufficiently low flow density so that the number Re_d, defined by parameters of undisturbed flow and by the diameter of probe d, becomes less than 200, then the viscosity and other effects connected with rarefaction of the medium start to affect the process of flow past the probe and $P'_{0\,meas}$ becomes different than the calculated value $P'_{0_{Id}}$ connected with parameters of undisturbed flow P_{st} and M by the formula of Rayleigh. This phenomenon was studied (mainly experimentally) by a number of authors [1-3] who obtained the dependence of the deviation $\frac{P_{0_{meas}}}{P'_{0_{ID}}}$ on the number Re_d, which allows us to introduce corrections to the readings of the probe for determination of parameters of undisturbed flow by the formula of Rayleigh. In connection with the fact that total pressure measured by the probe of total pressure in supersonic flow is determined by the structure of flow with flow past its nose part, the influence of rarefaction of the medium starts to be evident when the thickness of the shock wave becomes commensurable with its separation from the nose part of the probe and with the boundary layer, as a result of which it is impossible to consider the jump as a break accurately satisfying the relationship of Hugoniot. According to the classification of reference [4], the latter takes place in regimes of mixed and transitional layers, so that for the criterion of rarefaction of the medium can be taken the relation

$$\frac{\lambda_1}{d} \sim \frac{\lambda_2}{\Delta} \sim \frac{M_1}{\sqrt{Re_d}}.$$

It is necessary to note that experimental data presented in references [1-3] show the essential dependence of the readings of the probe on the number Re_d and the form of its nose part; however, they do not allow us to establish the influence of number M_1 of the incident flow (because of the extremely narrow range of change of M_1). Considering the essential dependence of the intensity of the shock wave on the number M_1, and also the experimental data of other authors for the study of pressure on the surface of blunt bodies in supersonic rarefied flows [5], one should expect that the number M_1 has to affect the readings of probes of total pressure when Re_d = const.

In connection with the fact that probes of total pressure are designed for study of the field of flow in nozzles and jets, the question about the possible influence of the geometry of the probe (mainly its diameter) on the measured profile of total pressure in an axially symmetric nozzle was investigated. The latter became especially urgent because by a number of authors was noted the appearance of "collapse" of total pressure near the axis of the nozzle, i.e., displacement of the maximum magnitude of total pressure in the direction from the axis to the wall. This phenomenon was considered to be a result of the influence of the measuring probe on the profile P_0' at sufficiently large diameter d ($d \geqslant 0.25\delta$).

For carrying out of investigations we used the vacuum gas-dynamic installation, allowing us to obtain a stationary rarefied flow of air at supersonic speeds (M_1 = 4.3 to 6.5) and low static pressures (P_1 = -20 to 6 microns of mercury). The diagram of the installation is shown in Fig. 1. The main elements of the installation are: vacuum chamber with pumping system, mixing chamber with preheater, and supersonic nozzle. During the operation of the installation the previously dried air proceeds through the regulator of consumption into the mixing chamber, where heating to a definite temperature T_{00} is possible, ensuring the absence of condensation during adiabatic expansion of the air in the nozzle and in the vacuum chamber. The necessary temperature of heating of air was determined by calculations by means of the constitution diagram for the given nozzle at the given parameters P_{00}, P_v and P_{sec}, where P_{00} is the pressure in the mixing chamber, P_v is the pressure in the vacuum chamber, P_{sec} is the pressure on the nozzle section. For obtaining of supersonic flow in vacuum chamber were used axisymmetric conical nozzles designed for numbers M_{sec} = 4.3 to 5.5 (taking into account the possible build-up of a boundary layer) with further growth of M_1 to 6.5 by broadening of the stream in the vacuum chamber. The geometric dimensions of nozzles and parameters of flow on the section and in the mixing chamber are presented in Table 1.

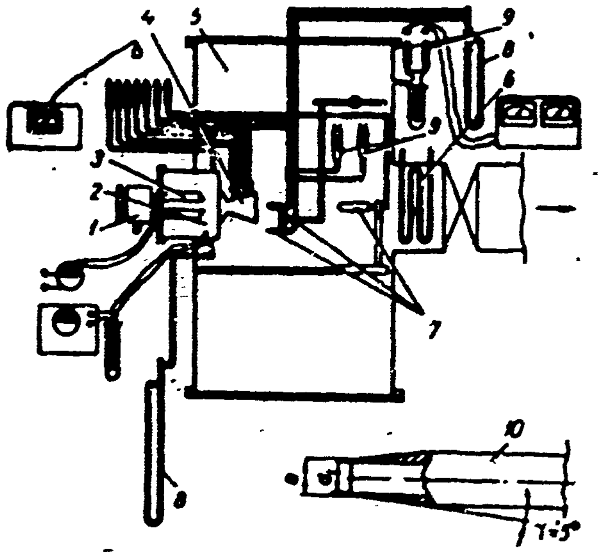

Fig. 1. Diagram of vacuum aerodynamic installation:
1) accumulator; 2) mixing chamber; 3) preheater; 4) nozzle; 5) vacuum chamber; 6) refrigerator; 7) probes of total pressure; 8) oil pressure gage; 9) manometric lamps; 10) diagram of probe of total pressure, d = 0.65 to 15.2 mm, d_1/d = 0.85 to 0.9.

TABLE 1

The Geometric Dimensions of Conical Nozzles and Parameters of Flow on the Nozzle Section and in the Mixing Chamber (χ = 1.405).

Диаметр среза, мм (a)	(b) Длина сверхзвуковой части сопла		(c) Расчетное число M на срезе	(d) Параметры адиабатно заторможенного потока		(e) Статическое давление на срезе, мк рт. ст.	(f) Измеренное число M на срезе
	(g) L [мм]	(h) $\frac{S_{ср}}{S_{кр}}$		T_{00}, °K	(i) p_{00}, мм рт. ст.		
60	80	62,4	6,3	293	4—6	16—17	4,3—4,7
63	80	158	7,8	293	7—9	10—13	5,3—5,5

Key: (a) Diameter of section mm; (b) Length of supersonic part of nozzle; (c) Calculated number M on section; (d) Parameters of adiabatic decelerated flow; (e) Static pressure on section microns of mercury; (f) Measured number M on section; (g) L[mm]; (h) S_{sec}/S_{cr}; (i) P_{00}, mm of mercury.

For preliminary calculation of the boundary layer and parameters of flow on the section of the axially symmetric nozzle was used an integral relationship of Karman analogous to the methodology of reference [6]. Check of the calculated data was carried out by the results of measurements of static pressures along the wall of the nozzle P_{st}, pressure in mixing chamber P_{co}, and also the total pressure P_o, measured by a probe of total pressure (at $Re_d \geqslant 300$) along the axis of the nozzle and in certain sections near the section. Measurement of pressures in range $10^{-3} - 6 \cdot 10^{-1}$ mm Hg was done by manometric lamps [9]. Pressures in the mixing chamber were measured by an oil manometer.

Results of experimental investigation of parameters of flow of rarefied air during expiration from nozzles are presented in Fig. 2 and in Table 1. In Fig. 2 are represented calculated values of number M in the central point of the section of nozzle No. 2, obtained by the formula of Rayleigh and by the formula of isentropic expansion with the use of experimental data P_{st}, P_o', depending upon the pressure in the mixing chamber. As can be seen from this graph, the calculated values of number M, obtained by two formulas, coincide only at certain values P_{oo} (for a given nozzle $P_{oo_{opt}} = 6$ to 10 mm Hg). Consequently, only for the given values of initial pressure on entrance into the nozzle of the given geometry is possible the existence on the nozzle section of the isentropic flow core. At pressures in the mixing chamber, less than $P_{oo_{opt}}$, the influence of viscosity extends to the entire field of flow near the nozzle section, but at $P_{oo} > P_{oo_{opt}}$ on the nozzle section is possible the appearance of a system of oblique compression shocks that leads to disturbance of the isentropic flow core.

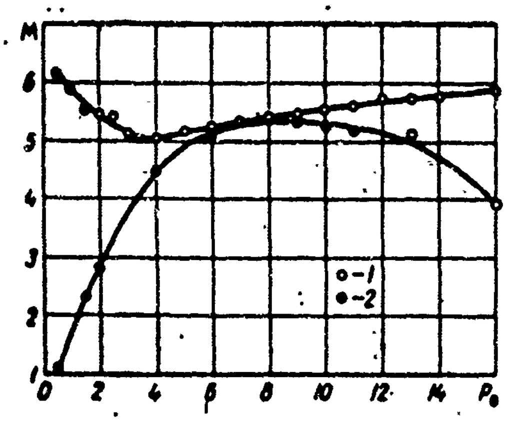

Fig. 2. Calculated values of number M in the central point of section of nozzle at different values of pressure P_0 (mm Hg) in mixing chamber (nozzle No. 2):

$$1 - M = f_1\left(\frac{P_0'}{P}\right); \quad 2 - M = f_2\left(\frac{P_{st}}{P_0'}\right)$$

From the presented data it follows that extent of the isentropic uniform flow core is sufficient for investigation of flow past the probe of diameter $d \leqslant 15$ mm. Analogous **investigations,** carried out for other nozzles, allowed us to determine the optimum range of P_{00} and the extent of the isentropic uniform flow core.

Investigations were conducted in the regime of insignificant underexpansion, so that the static pressure on the nozzle section was more somewhat higher than the pressure in the vacuum chamber that was attained by continuous exhaust of air from the vacuum chamber with the help of a group of vacuum pumps, ensuring the stationary operating conditions of the installation. In investigations was used a series of geometrically similar probes with a thin wall and angle of slant $\gamma = 5°$, with apertures of different diameter, and the ratio of the diameter of aperture d_1 to the external diameter $\underline{d}$ of the probe was kept approximately equal to 0.85 with accuracy of $\pm 5\%$. The investigated probes with the help of a special mobile coordinate mechanism could be moved to different points of the flow with accuracy up to

0.2 mm. Conductance of the system of tubes, connecting the probes in order with one and the same vacuum data unit, allowed us to produce measurements of pressure with a time delay not greater than 3 min for the lowest pressures. For explanation of the influence of the diameter of the probe (number Re_d) on the measured magnitude of total pressure, probes of different diameter were placed consecutively in one and the same point of stationary supersonic flow. For determination of the influence of number M on the measured magnitude of total pressure for a given probe, was produced a variation of parameters of the undisturbed flow by three methods: change of geometry of the nozzle; change of initial parameters of flow before the nozzle; and movement of one and the same probe along the axis of the isentropic flow core.

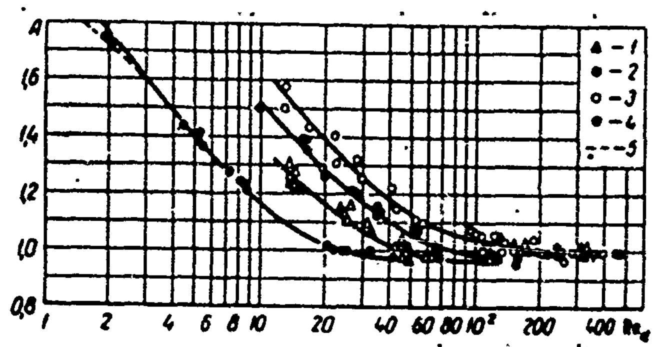

Fig. 3. Dependence of ratio $\frac{P'_{0\,meas}}{P'_{0\,Id}} = A$ on the number Re_d at different numbers M_1: 1) M_1 = 4.4 to 4.6; 2) 5.5 to 5.7; 3) 6.3 to 6.5; 4) 1.82 to 1.99 [3]; 5) 1.23 [3].

TABLE 2

Magnitudes of Measured Total Pressure by Tubes of Total Pressure with Different Diameter d.

(a) Параметры потока		(b) P'_0, мк рт. ст.					
M	(c) Re на 1 мм	d=15,2 мм	10,2 мм	5,2 мм	2,15 мм	1,15 мм	0,65 мм
4,80	27,5	445	—	435	440	480	520
4,91	26,2	410	—	387	405	460	490
5,04	25,5	370	—	360	385	435	470
5,10	24,6	350	—	340	365	—	457
5,53	24,4	267	272	273	285	335	348
5,62	23,5	253	253	255	275	315	330
5,67	23,5	240	242	247	260	303	315
5,83	22,0	220	210	222	240	270	290

KEY: (a) Parameters of flow; (b) P'_0, microns of mercury; (c) per 1 mm.

Certain experimental data, represented in Table 2 in the form of dependence of total pressure on the diameter of the probe, show that the influence of the diameter of the probe on its reading (in investigated range of variation of parameters of flow) starts to be evident for diameters of probes, smaller than 2 mm, abruptly increasing at d < 1 mm. Processing of obtained experimental data for all investigated regimes and nozzles in the form of dependence of $\frac{P'_{0\,meas}}{P'_{0\,Id}}$ on Re_d for different numbers M_1 (number M_1 was taken as a parameter) is shown in Fig. 3.

Besides measurements of total pressure along the axis of the nozzle, was conducted an investigation of the field of flow on the nozzle section by the very same probes at different initial pressures before the nozzle. Results of measurements, presented in Fig. 4, show the strong influence of the diameter of the probe on the magnitude of its reading; however the diameter of the probe does not affect the character of the measured profile of total pressure on the nozzle section, which is determined only by the regime of expiration: the initial pressure and temperature in the mixing chamber.

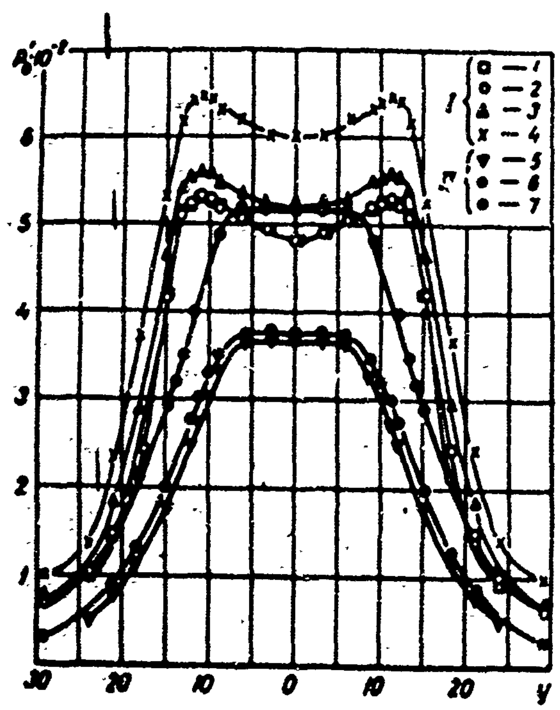

Fig. 4. Profiles of total pressure on the nozzle section No. 1 (along axis measured by probes of total pressure of different diameter for two flow regimes I. P_{00} = 8 mm Kg: 1) d = 5.2 mm; 2) 2.15; 3) 1.15; 4) 0.65; II. P_{00} = 4 mm Hg: 5) d = 5.2 mm; 6) 2.15; 7) 0.65.

The carried out investigations allowed us to establish the main regularities of the influence of rarefaction of supersonic flow on the deviation of total pressure, measured by a probe of full pressure, from value obtained by the formula of Rayleigh (for ideal compressible fluid) for the given number M_1. Criterial processing of experimental data, shown in Fig. 3, shows that the reading of a probe of full pressure, besides Re_d, is essentially influenced by number M_1; and for the constant number Re_d the more strongly the measured total pressure differs from the corresponding ideal value, the bigger the number M_1 of undisturbed flow. In connection with, this the obtained experimental data were represented in the form of dependence on he criterion of rarefaction of the medium of $\frac{Re_d}{M}$ (Fig. 5). It turned out that with such selection of the determining parameter, the experimental data satisfactorily lie on one and the same curve.

It is necessary to note that the data presented in work [3] for an analogous probe satisfactorily agree with the obtained results (Fig. 5). The established experimental dependence can be considered as a calibration curve for probes of total pressure of the given configuration, which gives us the possibility to investigate the structure and parameters of rarefied supersonic flow corresponding to the investigated range Re_d/M.

The qualitative character of the obtained dependence is determined by the action of two processes: 1) increase of influence of viscosity on the flow near the surface of the blunt body (nose part of the probe) leading, according to theoretical investigation [8], to a decrease of the total pressure of near the stagnation point; 2) a change of structure of the shock wave with increase of rarefaction, accompanied by a decrease of nonreversible losses during transition through the shock front, and consequently, increase of pressure at the stagnation point [4]. According to obtained experimental result the first process is determining for sufficiently large numbers $Re_d \simeq$ $\simeq$ 30 to 50, corresponding to the regime near to slipping; upon decrea of Re_d in the shown range of numbers M_1 the main influence appears to be the second process, and at $Re_d \simeq$ 1 to 4 the magnitude of total pressure approaches the maximum possible magnitude, corresponding to the molecular regime of flow during the absence of a shock wave [7]

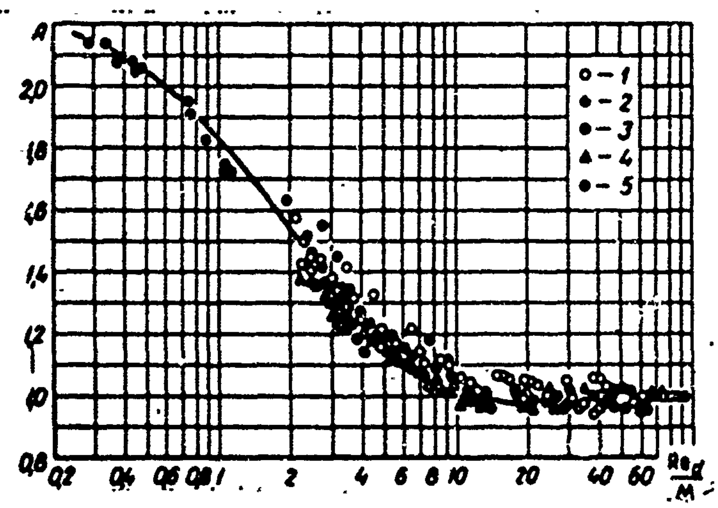

Fig. 5. Dependence of ratio $\frac{P\delta_{meas}}{P\delta_{Id}} = A$ on the criterion of rarefaction of the medium:
1) M = 6.0 to 6.5; 2) 5.5 to 5.9; 3) 5.0 to 5.4; 4) 4.3 to 4.9; 5) 1.23 to 1.99.

Investigated probes were used for measurement of the profile of total pressure on the nozzle section, and the ratio of the diameter of the probe to the thickness of the boundary layer changed in a wide range from 0.04 to 0.32.

The experimental data in Fig. 3 show that the profile of total pressure on the nozzle section does not in practice depend on the diameter of the probe. Consequently, the appearance of a "dip" of total pressure near the axis of the nozzle is not connected with geometric relationships of the diameter of probe and the thickness of the boundary layer, but depends on the flow regime. It is characteristic that the decrease of initial pressure P_{OO} for a given nozzle, i.e., increase of rarefaction of flow, leading to noticeable widening of the boundary layer and to a decrease of the isentropic core, leads to a qualitative change of the profile of total pressure — the disappearance of the "dip" of total pressure near the nozzle. The explanation advanced by the author [2] of the "dip" of total pressure near the axis of the nozzle as a result of interaction of the probe with the boundary layer on the wall of the nozzle at $d \geqslant 0.25 \delta$ is refuted by the present investigation.

Comparison of the measured static pressure on the wall of the nozzle with the calculated value on the axis of the nozzle shows that the appearance of a "dip" of total pressure near the axis of the nozzle is connected with the incalculability of the regime of expiration from the nozzle, i.e., with the appearance of oblique compression shocks in the regime of insignificant overexpansion.

Designations

P — static pressure; M — Mach number; Re — Reynolds number; P_O' — stagnation pressure behind the normal shock in supersonic flow; λ — length of free path of molecules in free flow; δ — thickness of boundary layer; d — diameter of probe; Δ — separation of shock wave from the nose part of the probe; 1 — corresponds to the parameters in free flow; 2 — corresponds to parameters after the shock wave; 00 — corresponds to parameters in adiabatically braked flow.

Summary

The investigations conducted show that the deviation of readings of impact-pressure probes in a supersonic rarefied flow from the ideal value depends not only on Re_d, as is shown in [1, 2], but also on M_1. When the parameter Re_d/M is used, the one curve satisfactorily correlates all the experimental data.

The relation $P'_0/P'_0 = f(Re_d/M)$ obtained may be considered as a calibration curve when parameters of a rarefied supersonic air flow are determined by impact-pressure probes of the given configuration and also makes it possible to define the change in a structure of a normal shock wave.

It is established that the probe diameter in the range investigated (d/δ = 0.04 to 0.32) does not influence the character of an impact-pressure profile measured. The appearance of a "dip" in impact pressure on the jet axis is a flow property dependent on flow conditions and nozzle geometry.

Literature

1. S. A. Schaaf. Heat Transfer...a Symposium 1952, Engineering Research Inst. University of Michigan, 1953.

2. W. A. Clayden. Rarefied Gas Dynamics, Proc, of the First Inst. Symposium, Nice, 1960, Pergamon Press, London, Oxford, New-York, Paris.

3. F. C. Hurlbut. Rarefied Gas Dynamics, Proc. of the First Inst. Symposium, Nice, 1960, Pergamon Press, London, Oxford, New-York, Paris.

4. R. Probstein and N. Kemp. Mechanics, No. 2 (66), 1961.

5. Fundamental of Gas Dynamics. Ed. H. W. Emmons, Vol. III, 1958.

6. G. H. Bocker. J. Aeron. Sci., 21, No. 1, 1954.

7. V. K. Lyu. Mechanics, No. 4 (56), 1959.

8. Kh. Sh. Tzyan. Collection. "Gas Dynamics", Foreign Literature Publishing House, 1950.

9. Ye. A. Penchko. Instruments and technology of experiment, No. 1, 1961.

Institute of Mechanics, Academy of
Sciences USSR, Moscow.

3 August 1962

DISTRIBUTION LIST

DEPARTMENT OF DEFENSE	Nr. Copies
HEADQUARTERS USAF	
AFCIN-3D2	1
OTHER AGENCIES	
CIA	5
DIA	4
AID	2
NASA	1
AFCRL (CRXLR)	1

MAJOR AIR COMMANDS	Nr. Copies
AFSC	
TDBTL	5
TDBDP	11
TDGS	1
TDBMT	10
TDT	2
TDEPA	1
SSD (SSF)	2
AFFTC (FTY)	1
AFWL (WLF)	1
ASD (ASFA)	2