Arch. Mech., 33, 4, pp. 501-510, Warszawa 1981

Experimental investigation of shock-wave structure in hydrogen-xenon mixture

A. S. GMURCZYK and Z. A. WALENTA (WARSZAWA)

THIS WORK is the continuation of the earlier investigation of the shock wave structure in the binary mixture of gases with disparate molecular masses. The experimental results of shock wave structure in a hydrogen-xenon mixture are presented. It was interesting to investigate the influence of the rotational degrees of freedom of one of the components on the shock wave structure, hence hydrogen was chosen as a light gas thanks to the very long zone of excitation of rotational degrees of freedom. The experiments were performed in a shock tube with the simultaneous use of the electron gun and laser interferometer. The humped density distribution of the light component, similar to that of the He — Xe mixture was observed. This kind of density profile of xenon, at low (about 1%) concentration, also was observed. Moreover it was found that the relaxation zone of excitation of rotational degrees of freedom depends weakly on the existence of a heavy gas.

Prezentowana praca jest kontynuacją wcześniejszych badań struktury fali uderzeniowej w podwójnej mieszaninie gazów o dużym stosunku mas cząsteczkowych. Przedstawione są wyniki badań experymentalnych w mieszaninie wodór-ksenon. Interesujące było zbadanie wpływu istnienia rotacyjnych stopni swobody jednego ze składników na strukturę fali uderzeniowej; wybrany został wodór ze względu na bardzo długi obszar wzbudzania rotacyjnych stopni swobody. Badania przeprowadzone zostały w rurze uderzeniowej przy jednoczesnym użyciu dwóch metod pomiarowych, tj. działka elektronowego i interferometru laserowego. Zaobserwowany został charakterystyczny «garbaty» rozkład gęstości lekkiego składnika, podobny do rozkładu w mieszaninie He—Xe. Tego typu profil gęstości ksenonu zaobserwowano również dla niewielkich (rzędu 1%) jego zawartości w mieszaninie. Ponadto stwierdzono niewielki wpływ obecności ciężkiego składnika na obszar wzbudzania rotacyjnych stopni swobody.

Предложенная работа является продолжением более ранних исследований структуры ударной волны в двойной смеси газов с большим отношением молекулярных масс. Представлены результаты экспериментальных исследований в смеси водород-ксенон. Интересным являлось исследовать влияние существования ротационных степеней свободы одного из компонентов на структуру ударной волны, и поэтому избран водород, из-за большой области возбуждения ротационных степеней свободы. Исследования проведены в ударной трубе, при одновременном использовании двух измерительных методов т.е. электронной пушки и лазерного интерферометра. Наблюдалось характеристическое „горбатое" распределение плотности легкого компонента, аналогичное тому, которое наблюдалось в смеси He — Xe. Этого типа профиль плотности ксенона наблюдался тоже, для небольших (порядка 1%) его содержаний, в смеси. Кроме этого обнаружено небольшое влияние присутствия тяжелого компонента на область возбуждения ротационных степеней свободы.

1. Introduction

A SHOCK wave is a very convenient object for studying nonequilibrium processes in gases thanks to very strong gradients of the parameters inside its structure. This was used by many investigators to study nonequilibria of vibrational degrees of freedom of the molecules, as well as various kinds of chemical nonequilibria. More recently it was used to investigate nonequilibria of rotational and translational degrees of freedom in pure gases and gas mixtures [1, 2, 3, 4, 5].

In our laboratory the experiments on the structure of shock waves in binary mixtures of disparate mass gases have been carried out for several years.

The papers published up to date were concerned only with mixtures of noble gases. The experiments reported in the present paper were extended to mixtures containing one diatomic component, hydrogen. At the same time the technique of the experiment was considerably improved and enabled us to answer conclusively certain questions posed in the previous papers [6, 7].

Concurrently with the experiment, theoretical investigations were also performed in order to enable proper understanding of the observed phenomena. The presently available theoretical results [8, 9, 10] are concerned with mixtures of noble gases. The investigations for a more general case are in progress.

Although this paper is a continuation of the papers published previously, we will repeat here certain points in order to make this work easier to read.

2. Description of experiments

The experiments were performed in a low density shock tube 250 mm in diameter and 17 m long.

The shock tube was equipped with six heat transfer gauges for measurement of the shock velocity at various distances from the measuring section. Runs for which the shock velocity were not sufficiently uniform were rejected. To maintain the necessary purity of the experiment the tube was pumped down to at least 10^{-5} mm Hg before the each run. The mixtures were made from spectrally pure gases in a special tank, at least one hour before the run.

The only magnitude we were able to measure was the gas density. We aimed at obtaining it for each component of the binary gas mixture separately and therefore we made two independent measurements using the electron gun and the laser interferometer.

The idea of using two independent measurements to obtain the density profiles in component gases is attributed to BARCELO [11]. This author used, however, two electron beams with different energies; the method proved to be not sufficiently sensitive so as to provide meaningful results.

The scheme of the experiment is shown in Fig. 1. The same type of instrument setting was used in our earlier experiments [6, 7] but some important modifications were introduced. The main modification was shielding the interferometer reference beam in a thin metallic tubing, which made the interferometer work on the absolute basis. This leads to better accuracy of the interferometer measurements due to the reduction of the influence of the reading errors.

Apart from that, the length of the test beam of the interferometer was decreased to 70 mm and the length of the electron beam was increased to the same value. The value of 70 mm was chosen because it allows to neglect the influence of the shock-wave curvature, giving at the same time sufficiently strong signals. As the lengths of the test beams were equal, any remaining influence of the shock curvature cancelled out.

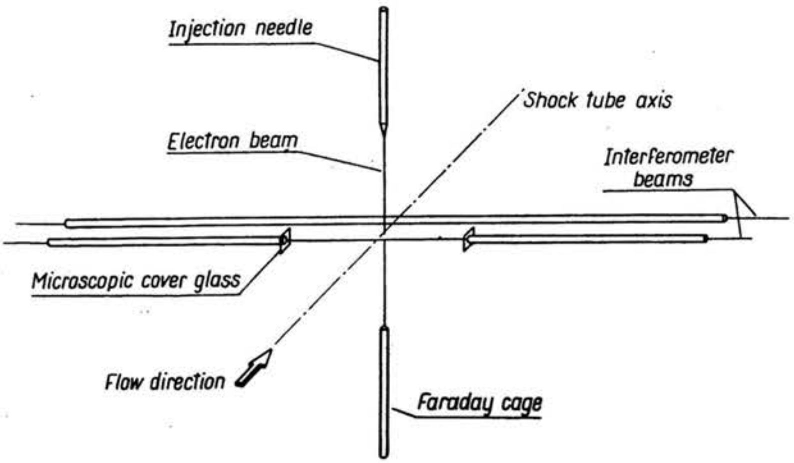

FIG. 1. Configuration of electron beam and interferometer beams.
Electron beam length $L_e = 70$ mm, interferometer beam length $L_i = 70$ mm, distance between interferometer and electron beams $D_{ie} = 5.6$ mm.

The density distributions of the component gases inside the shock wave were obtained by means of the following equations:

$$\varrho_1 = \varrho_i + C_1(\varrho_i - \varrho_e),$$
$$\varrho_2 = \varrho_e + C_2(\varrho_i - \varrho_e),$$

where ϱ_i and ϱ_e — quantities measured by the interferometer and electron beam respectively, ϱ_1 and ϱ_2 — densities of the component gases

$$C_1 = \frac{k + \frac{p_2 m_2}{p_1 m_1}}{n - k}, \quad C_2 = \frac{\frac{1}{n} + \frac{p_1 m_1}{p_2 m_2}}{\frac{1}{k} - \frac{1}{n}}, \quad k = \frac{Q_1 m_2}{Q_2 m_1},$$

Q — collision cross-section for electron scattering, m — molecular mass, p — pressure in front of the shock, n — ratio of the Gladstone–Dale constants.

The experiments reported in the present paper were performed in hydrogen-xenon and helium–xenon mixtures.

The purpose of repeating once again the results concerning helium–xenon mixtures with the improved experimental setup was to answer several unresolved questions which arose following our previous findings [6, 7].

In the experiments with the hydrogen–xenon mixture our aim was to learn about the influence of rotational degrees of freedom on the shock structure in such a mixture. Hydrogen was the obvious choice because its rotational relaxation time is longer than for any other gas and therefore the effects of the rotational degrees of freedom should be clearly visible.

The conditions of the experiments are summarized in Table 1.

Table 1.

1	2	3	4	5	6	7
He—Xe	3.45		0.3768			3.89
H_2—Xe	1.1	157.0	0.5884	0.5913	84.06	2.63
H_2—Xe	1.5	163.7	0.5007	0.5838	11.71	2.83
H_2—Xe	3.0	153.2	0.5019	0.6267	6.52	2.98
H_2—Xe	4.0	102.8	0.7294	0.9450	7.27	2.81
H_2—Xe	6.6	162.0	0.4375	0.6141	2.79	2.60
H_2—Xe	10.7	117.2	0.5650	0.8878	2.37	2.92

1 — mixture,
2 — mole fraction of heavy component,
3 — initial pressure of the mixture (μm Hg),
4 — mean free path of the mixture (mm),
5 — mean free path of the light component (mm), } in front of the shock,
6 — mean free path of the heavy component (mm),
7 — shock Mach number.

3. Results

3.1. Helium-xenon mixture

The typical shock-wave structure in the helium–xenon mixture, obtained in the present experiments, is shown in Fig. 2a. For the sake of comparison we show in Fig. 2b the shock-wave structure in the mixture of the same gases obtained previously [6, 7].

In Fig. 2b a very peculiar overshoot of the helium density over its downstream equilibrium value can be seen. We were unable to understand the presence of this overshoot and we suspected that it could be due to experimental inaccuracies.

From our present results (Fig. 2a) it is clear that the overshoot was an experimental artifact, most probably of correcting the influence of the shock wave curvature.

All other characteristic features of the shock structure, i.e. strong separation of the components and "humped" distribution of helium, can be noticed in both, old and new results.

There is some difference between the thicknesses of shock waves shown in Figs. 2a and 2b. This difference most probably can be attributed to the difference in gas mixture compositions.

3.2. Hydrogen–xenon mixture

Shock wave structures for several hydrogen–xenon mixtures with different volume concentration are shown in Figs 3–8. The qualitative features of these structures are similar to those in the case of helium–xenon mixtures. The density increase of the heavy component, xenon, lags behind that of the light one, hydrogen. For mixtures containing small amounts of xenon, the density distributions of the light component has clearly the humped

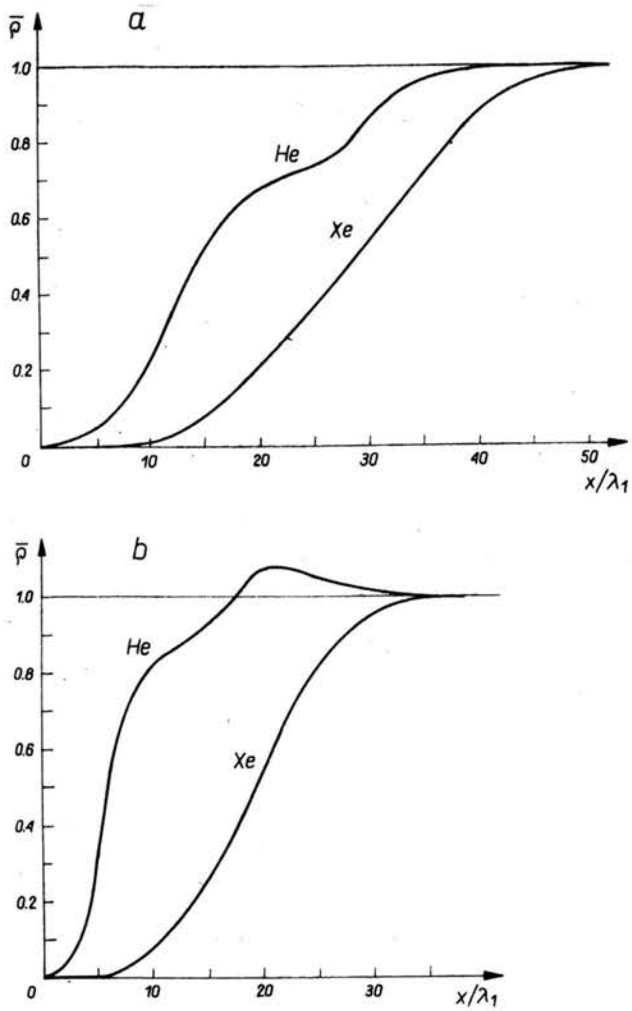

FIG. 2.a. Density distribution of helium and xenon in 3.45% Xe — 96.55% He mixture; $M = 3.89$, $\lambda_1 = 0.3768$ mm. b. Density distribution of helium and xenon in 3.0% Xe — 97.0% He mixture; $M = 3.89$, $\lambda_1 = 0.46$ mm.

structure, i.e. the initial sharp rise is followed by a relaxation zone where the rise of density is slower.

For mixtures with larger amounts of xenon this humped structure disappears and the shock wave structures in each component look like those in pure gases.

There are, however, some important differences between shock structures in He—He and H_2—Xe mixtures.

First, the total thickness of the shock zone in the H_2—Xe mixture is about two times larger than in the He—Xe mixture.

Second, the xenon density profiles in the H_2—Xe mixtures follow the shape of hydrogen density profiles; in particular, for low concentration of xenon its density profiles have a distinct humped structure.

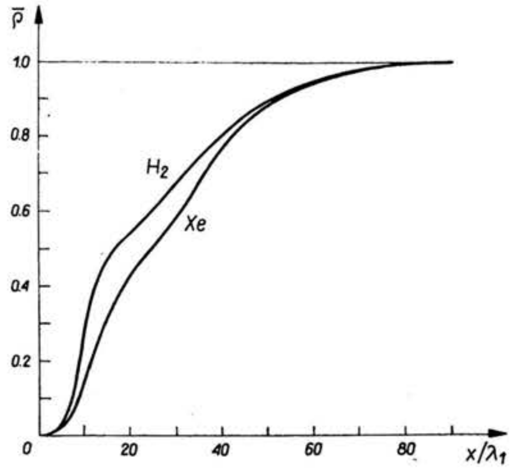

FIG. 3. Density distribution of hydrogen and xenon in 1.1% Xe — 98.9% H_2 mixture, $M = 2.63$, $\lambda_1 = 0.5884$ mm.

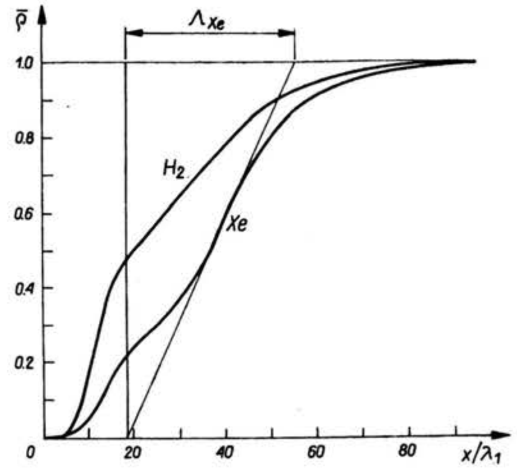

FIG. 4. Density distribution of hydrogen and xenon in 1.5% Xe — 98.5% H_2 mixture; $M = 2.83$, $\lambda_1 = 0.5007$ mm.

The difference in the thickness of the shock can be explained by the combined effects of a larger molecular-mass ratio and a long relaxation time of the rotational degrees of freedom of hydrogen. The reason for the second difference is less obvious. At first we suspected that this structure was an artifact caused by the use of inaccurate values of the electron scattering cross-sections and Gladstone–Dale constants which were assumed for calculations. However, this possibility was ruled out by auxiliary calculations in which the values of these constants were varied within reasonable limits.

The humped density distribution of the light components explains similarly to the case of the He—Xe mixture. At low concentrations of the heavy species the initial part of the shock wave structure in the light component is very weakly affected by the presence

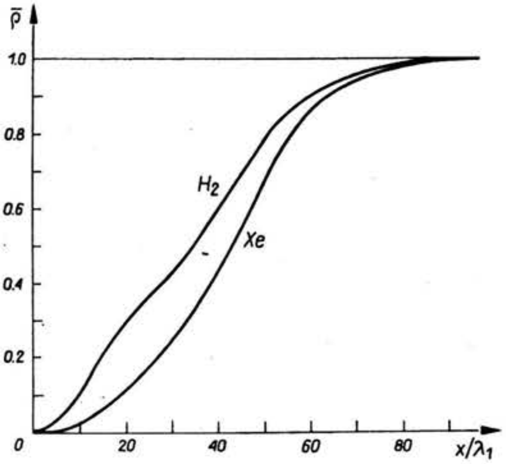

FIG. 5. Density distribution of hydrogen and xenon in 3.0% Xe — 97.0% H_2 mixture; $M = 2.98$, $\lambda_1 = 0.5019$ mm.

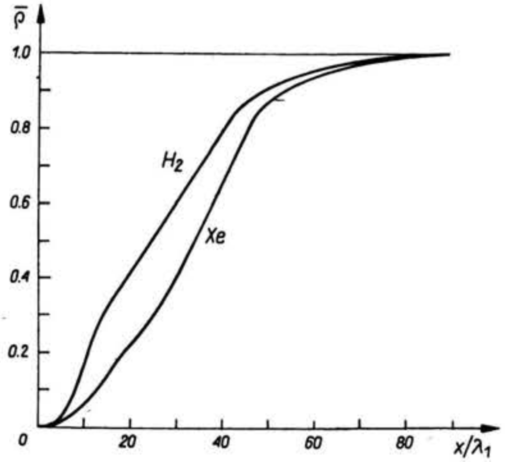

FIG. 6. Density distribution of hydrogen and xenon in 4.0% Xe — 96.0% H_2 mixture; $M = 2.81$, $\lambda_1 = 0.7294$ mm.

of the heavy atoms. As in pure gas, the initial fast density jump occurs, followed by a longer relaxation zone, where energy is transmitted to both rotational degrees of freedom and to the atoms of the heavy component.

The compression of the heavy component at its low concentrations is due to collisions with light atoms only (the frequency of collisions between heavy atoms is negligibly small).

The humped structure of the xenon density distributions can be explained assuming that the coupling between translational degrees of freedom of the hydrogen molecules and xenon atoms is stronger than between translational and rotational degrees of freedom of hydrogen molecules. If this is the case, the compression of xenon starts earlier than the excitation of rotational degrees of freedom of hydrogen. Further, when the latter

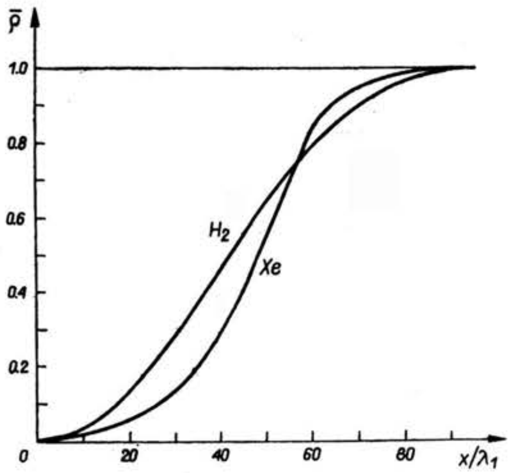

FIG. 7. Density distribution of hydrogen and xenon in 6.6% Xe — 93.4% H_2 mixture; $M = 2.60$, $\lambda_1 = 0.4375$ mm.

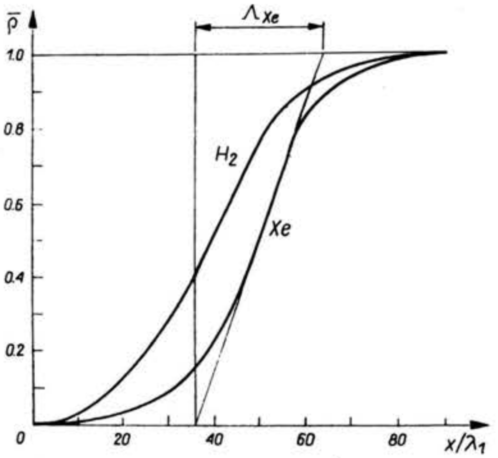

FIG. 8. Density distribution of hydrogen and xenon in 10.7% Xe — 89.3% H_2 mixture; $M = 2.92$, $\lambda_1 = 0.5650$ mm.

process is initiated, the amount of energy available for xenon atoms is decreased and therefore its compression slows down.

There is one more interesting feature of the H_2—Xe shock waves. For the mixture containing 6.6% xenon, an intersection of the density curves of hydrogen and xenon occurs. This means that the relative value of the concentration of the heavy species is locally higher than its equilibrium value. Such a phenomenon is rather unexpected. One might try to explain it on the basis of the differences of suitable relaxation times, however, we cannot rule out the possibility of its being an artifact.

For a more quantitative comparison of the present results with the helium–xenon case we use the formerly introduced concept of the relative component shock thickness

RCST. This is the ratio of the component shock thickness (defined in Figs. 4 and 8) to the mean free path in the corresponding component gas under the pressure equal to its partial pressure in front of the shock.

The RCST's of xenon in the H_2—Xe and He—Xe mixtures in terms of mole fraction and mass fraction of xenon are shown in Figs. 9 and 10.

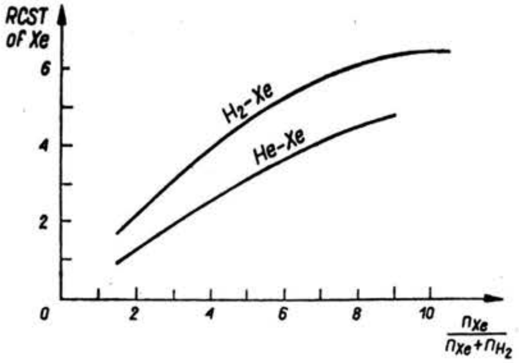

FIG. 9. Relative component shock thickness of xenon in He—Xe and H_2—Xe mixtures in terms of xenon mole fraction.

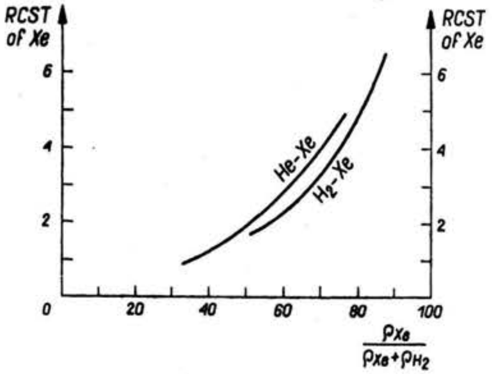

FIG. 10. Relative component shock thickness of xenon in He—Xe and H_2—Xe mixtures in terms of xenon mass fraction.

For the same mole fraction of the heavy component (Fig. 9) the RCST of xenon in the H_2—Xe mixture is larger than for the He—Xe mixture. This is self-explanatory since the hydrogen molecules are less massive than the helium ones and therefore more collisions are necessary to compress the heavy component.

For the same mass fraction of xenon (Fig. 10) its RCST in the H_2—Xe mixture is smaller than in the case of the He—Xe mixture. This can be attributed to the fact that the total cross-section for He—Xe collisions is larger than that for H_2—Xe collisions, the He—Xe collisions are "more efficient" than the H_2—Xe collisions.

4. Conclusions

The introduced modification of the experimental setup has greatly improved the accuracy of the measurements. It was thus possible to eliminate certain artifacts appearing in the former experimental results.

The most interesting result of the present hydrogen-xenon experiments is the humped distribution of density of the heavy component, similar to that of the light component. This phenomenon was not observed in the mixture of monotonic gases and is tentatively explained by the the redistribution of energy between translational and rotational degrees of freedom of the molecules.

Another interesting feature of the obtained shock structure is the intersection of density curves of the light and heavy component. This is, however, not sufficiently well substantiated — either experimentally or theoretically. Its existence will have to be verified in future investigations in an experimental and theoretical manner.

References

1. R. STREHLOV, A. COHEN, *Limitations of the reflected shock technique for studying fast chemical reactions and its application to the observation of relaxation in nitrogen and oxygen*, J. Chem. Phys., **30**, 1, 257–270, 1959.
2. F. ROBBEN, L. TALBOT, *Experimental study of the rotational distribution function of nitrogen in a shock wave*, Phys. Fluids, **9**, 4, 653, 1966.
3. A. K. MACPHERSEN, *Rotational temperature profiles of shock waves in diatomic gases*, J. Fluid Mech., **49**, 2, 337, 1971.
4. T. HOLTZ, *Measurements of molecular velocity distribution functions in an argon normal shock wave at Mach number 7*, Ph. D. Thesis, USC, 1–131, 1974.
5. L. N. HARNETT, E. P. MUNTZ, *Experimental investigation of normal shock wave velocity distribution functions in mixtures of argon and helium*, Phys. Fluids, **15**, 4, 1972.
6. A. S. GMURCZYK, M. TARCZYŃSKI, Z. A. WALENTA, *Shock wave structure in the binary mixtures of gases with disparate molecular masses*, Proc. of XI RGD Symp., Cannes 1978.
7. A. S. GMURCZYK, M. TARCZYŃSKI, Z. A. WALENTA, *Struktura fali uderzeniowej w mieszaninie gazów szlachetnych*, Prace IPPT, 609/178, Warszawa 1978.
8. M. BRATOS, R. HERCZYŃSKI, *Determination of intermolecular potentials via gas-dynamic measurements*, ICTAM Congress, Toronto 1980.
9. T. PŁATKOWSKI, *Application of the modified BGK equations to the shock wave structure in disparate mass mixtures*, Proc. of XI RGD Symp., Cannes 1978.
10. T. PŁATKOWSKI, Ph. D. Thesis, Warsaw University, Warsaw 1980.
11. B. T. BORCELO, *Electron beam measurements of the shock wave structure*, Ph. D. Thesis, Cal. Inst. of Techn., Pasadena 1971.

POLISH ACADEMY OF SCIENCES
INSTITUTE OF FUNDAMENTAL TECHNOLOGICAL RESEARCH.

Received November 17, 1980.