Microscopic structure of the Mach-type reflexion of the shock wave

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THE PURPOSE of the present work was to investigate the microscopic structure of the three-shock interaction region, generated in low-density shock tube during the Mach-type reflexion of a shock wave. The experimental conditions corresponded to the so-called "simple Mach reflexion". It was found that the diameter of the interaction region was equal to about 20 mean free paths in the gas ahead of the incident shock and outside this region all the three shocks were plane. The angle between the incident and reflected shock was in serious disagreement with the prediction of von Neumann's theory of the phenomenon. A possible reason for this was the flow nonuniformity in a low-density shock tube, whose presence is contrary to the assumptions of von Neumann's theory.

Celem pracy było zbadanie struktury mikroskopowej obszaru oddziaływania trzech fal uderzeniowych generowanych w rurze uderzeniowej w procesie odbicia się fali uderzeniowej. Warunki doświadczenia odpowiadały tzw. „prostemu odbiciu Macha". Stwierdzono, że średnica obszaru oddziaływania równała się 20 średnim drogom swobodnym w gazie przed falą padającą, a za tym obszarem wszystkie trzy fale uderzeniowe były płaskie. Kąt między falą padającą a odbitą odbiegał poważnie od przewidywań teorii von Neumanna. Przyczyną tej niezgodności mogła być niejednorodność przepływu w rurze uderzeniowej małej gęstości, niezgodna z założeniami teorii von Neumanna.

Целью работы являлось рассмотрение микроскопической структуры области взаимодействия трех ударных волн, генерированных в ударной трубе в процессе маховского отражения ударной волны. Условия эксперимента отвечали т. наз. „простому отражению Маха". Констатировано, что диаметр области взаимодействия равнялся 20 средним свободным пробегам в газе перед падающей волной, а за этой областью все три ударные волны были плоскими. Угол между падающей и отраженной волнами значительно отличался от предсказываний теории Неймана. Возможной причиной этого несовпадения могла быть неоднородность течения в ударной трубе малой плотности, несовпадающая с предположениями теории Неймана.

1. Introduction

WHEN an oblique shock wave strikes a solid wall, shock reflexion occurs. For small angles between the incoming shock and the wall one observes regular reflexion (Fig. 1a). For large angles regular reflexion is not possible since the reflected shock cannot deflect the flow by the same angle as the incident one and Mach-type reflexion occurs (Fig. 1b).

Within the frame of the ideal gas theory, J. VON NEUMANN first proposed the description of shock wave reflexion [1]. It is based on the following assumptions:

all shock waves in question are planar and therefore the Rankine-Hugoniot conditions hold,

the flow in all regions delineated by shock waves is uniform.

For regular reflexion the overall flow deflection is zero. For Mach-type reflexion the pressures on both sides of the contact surface, generated behind the triple point, are assumed
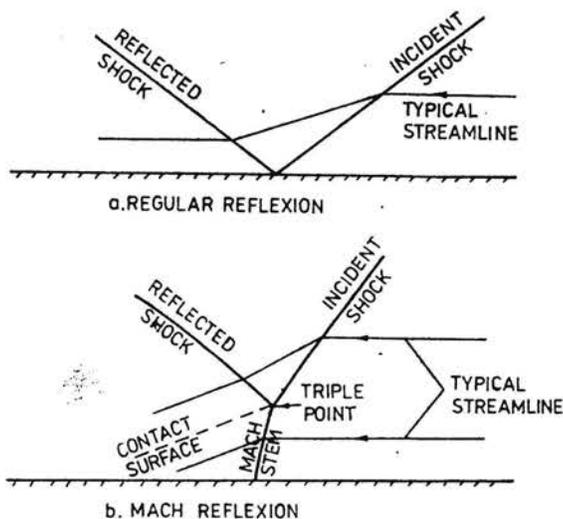
FIG. 1. Reflexions of oblique shock waves. a) Regular reflexion. b) Mach reflexion.

to be equal and also the directions of flow are parallel. These conditions make is possible to close the system of equations (the Rankine-Hugoniot conditions).

For strong shock waves the solution (although not always unique) exists and it is in fair agreement with experiment.

For weaker shock waves there is a certain range of parameters for which this system has no solution in spite of the fact that Mach-type reflexion is observed experimentally.

Although there is a large amount of experimental data related to the overall picture of the flow near the triple point, the detailed analysis of its vicinity has never been performed. There are only two papers treating the subject theoretically. The first dating from 1959, by STERNBERG [2], an attempt to resolve the problem of the Mach-type reflexion for weak shocks by taking into account the dissipation effects. The second, dating from 1977, by AULD and BIRD [3], gives only the qualitative picture of the flow obtained with the Monte Carlo method.

Thorough experimental analysis of the vicinity of the triple point can reveal the interesting features of the flow, especially for conditions in which the ideal gas theory does not predict its existence. Apart from that, such an analysis can guide future theoretical work.

In this paper, however, our aim is more limited. We present an experimental method of the analysis of the triple-point region for the so-called simple Mach reflexion (when the ideal gas theory does predict the existence of this reflexion) and we compare the obtained results with those of von Neumann's theory. In particular, the questions to be answered are:

how large is the region of interaction of the shocks?

are those shocks planar in the vicinity of the interaction region?

are the angles between the shocks equal to those calculated from von Neumann's theory?

2. Experiment

To answer these questions the experiments had to be performed in the rarefied gas conditions which enable resolving the details of the interaction region of the shocks.

In order to generate the shock waves, a low-density shock tube of the Department of Fluid Mechanics, Institute of Fundamental Technological Research, Polish Academy of Sciences [4] was used. The tube was cylindrical, 250 mm' in diameter and 17 meters long.
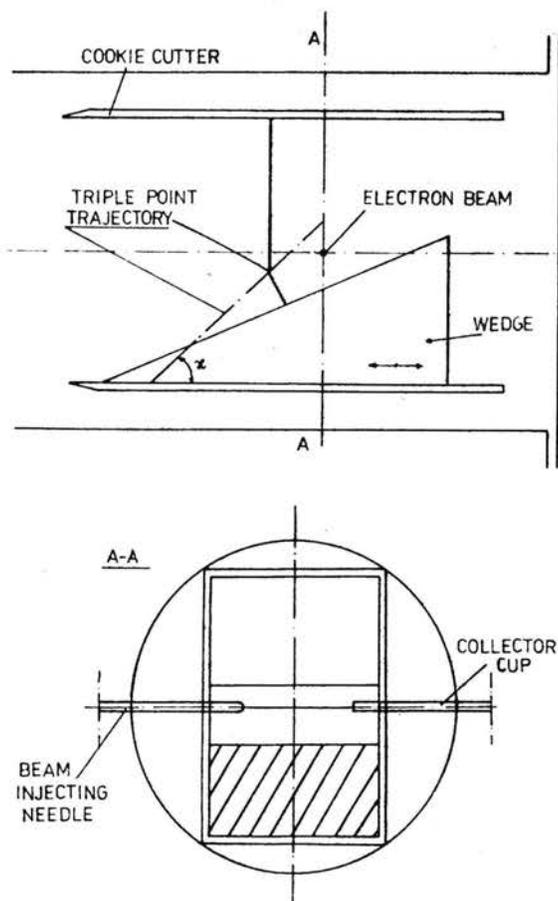

FIG. 2. Test section of the shock tube.

To maintain the planarity of the flow, a rectangular "cookie cutter" was placed in the test section of the tube (Fig. 2). Inside this cookie cutter a 25 or 15 degree wedge could be placed .The wedge could be shifted in the direction parallel to the tube axis.

The gas density inside the shock waves was measured with the standard electron beam attenuation technique. The beam was perpendicular to the tube axis and parallel to the wedge surface. To avoid the influence of the sidewall boundary layer on the measurements, both the beam injecting needle and the collector cup protruded deep into the test section (Fig. 2).

In a single run it was possible to obtain the density distribution along a straight line, parallel to the trajectory of the triple point (Fig. 2). To obtain the whole density field it was necessary to superimpose the results taken from several runs at various positions of the wedge with respect to the beam. Such a superposition was made possible by a very good repeatability of the runs (scatter of the measured shock velocities of the order of 1 per cent).

In order to obtain the value of the triple point trajectory angle for the 25° wedge, an additional set of runs was performed with the wedge moved closer to the tube axis.

The conditions of the experiment are summarized in the Table 1.

Table 1.

Experiment	I	II
Gas	Argon	Argon
Initial pressure	102 μmHg.	102 μmHg.
Initial mean free path	0.534 mm	0.539 mm
Shock Mach number	3.22	3.20
Wedge angle	25°	15°

3. Results

The results of the experiments are presented in Figs. 3 to 5. Figure 3 shows the gas density distributions along the lines parallel to the triple point trajectory for the 25° wedge. Figure 4 shows the "map" of the density field as calculated on the basis of Fig. 3.
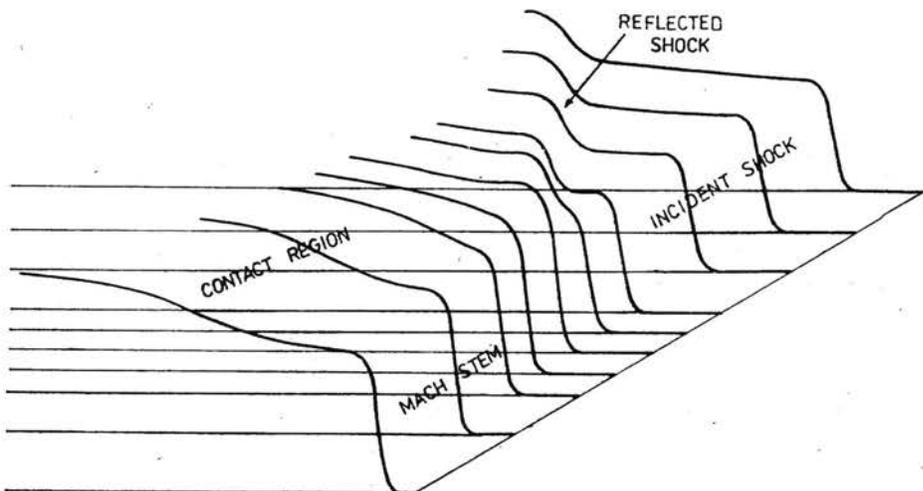

FIG. 3. Normalized density distributions along the lines parallel to the triple point trajectory (25° wedge).
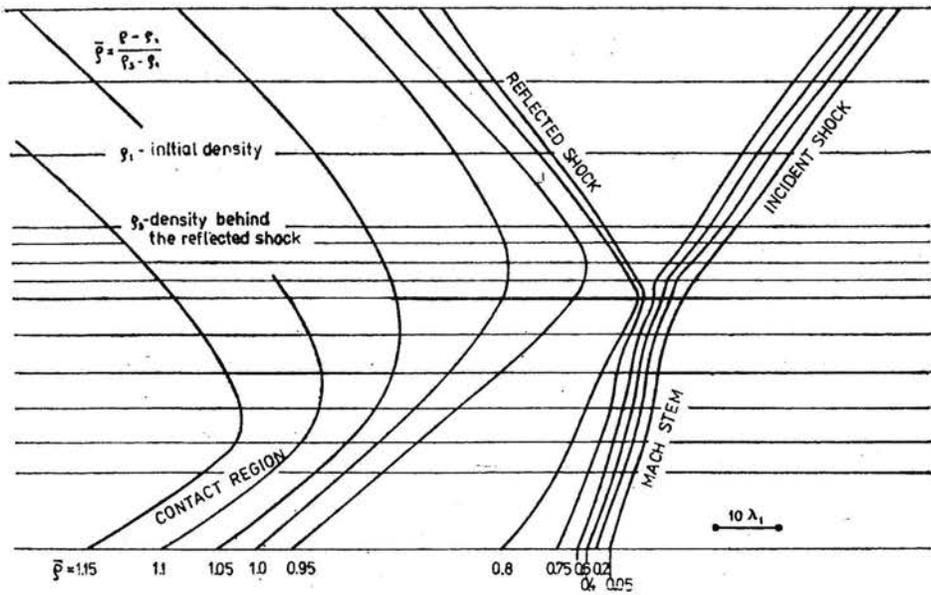
$$\bar{\rho} = \frac{\rho - \rho_1}{\rho_3 - \rho_1}$$

ρ_1 - initial density

ρ_3 - density behind the reflected shock

REFLECTED SHOCK

INCIDENT SHOCK

MACH STEM

CONTACT REGION

10 λ_1

$\bar{\rho} = 1.15$ 1.1   1.05   1.0   0.95   0.8   0.75 0.6 0.2   0.4 0.05

FIG. 4. Map of the density field for 25° wedge.

REFLECTED SHOCK

INCIDENT SHOCK

INITIAL FLOW DIRECTION

MACH STEM

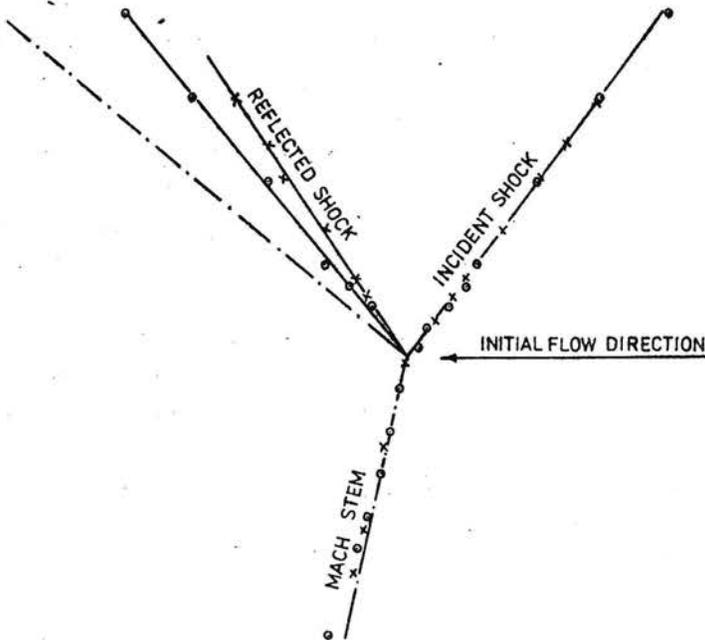FIG. 5. Positions of the inflection points of the density distribution curves. ⊙ — wedge in normal position; × — wedge moved towards the tube axis; —— · —— theoretical positions of the reflected shock and Mach stem.

In these two figures the three shocks, i.e. the incoming, the reflected and the Mach stem shocks are clearly visible. Between the reflected shock and the Mach stem a relatively broad region, a "contact surface", can also be seen. The area where the three shocks merge can be estimated to have a diameter of about 20 mean free paths in front of the incident shock.

Figure 5 shows the positions of the inflection points of the density distributions curves inside the shocks. In this figure it can be seen that all the three shocks are, as expected, planar. However, the angles between the shocks do not agree with the predictions of von Neumann's theory. In particular, the difference between the angles between the incident and reflected shocks obtained from the theory and experiment is about 14.5 and 20 degrees for the two positions of the wedge, respectively. This is much above the experimental inaccuracy estimated to be ± 2 degrees.

The most probable reason for this descrepancy is the flow nonuniformity between the incident and reflected shocks. Such nonuniformity, caused by the influence of the sidewall boundary layer, is always present in shock tube flows and is particularly important in low-density shock tubes [5].

According to the earlier calculations made by the author for regular reflexion of a shock wave, such a nonuniformity does influence the angle between the incident and reflected shocks. Depending on the flow parameters, this angle can be increased or decreased [6].

Since the flow between the reflected shock wave and the contact surface in the case of Mach reflexion is qualitatively similar to the flow between the reflected shock and the wall for regular reflexion, the influence of the flow nonuniformity in both cases should be similar.

Possibly, the discrepancies between theoretical and experimental data reported by OERTEL [7] and HORNUNG et al. [8] can also be attributed to the same factor. The question will require more detailed clarification.

In our experiment the discrepancy between the theoretical and experimental angle of the Mach stem remains within the limits of estimated inaccuracy. However, it might also be due to the influence of the boundary layer at the wedge surface [9].

It should be mentioned here that the process of data reduction is based on the assumed value of the angle between the trajectory of the triple point and the wall (Fig. 2).

As mentioned previously, in order to evaluate this angle, two sets of runs at different positions of the wedge were performed.

The angle obtained differs by about 0.5 degree from the value obtained in the experiment at high gas density performed by BEN DOR [10]. For data reduction the measured value of this angle was used.

It should be noted that the trajectory of the triple point extrapolated towards the wedge nose did not go through it (Fig. 2), contrary to the reported results in high density experiment [10, 11, 12, 1]. The reason probably lies in some complicated flow phenomena close to the wedge nose which, at high densities, are confined to sufficiently narrow space not to be noticed.

4. Conclusions

The reported experiment gives some insight into the details of the flow in the region of interaction of three shocks generated at the Mach-type shock reflexion. The results obtained agree in principle with the predictions made on the basis of von Neumann's theory and with the experiments performed at higher gas densities. The observed discrepancies are estimated to be due mainly to flow nonuniformities in the regions between the shocks. In high density experiments these nonuniformities are much weaker, but even then their presence can affect the shock waves. The presence of these nonuniformities contradicts the assumptions accepted in von Neumann's theory.

The present results are also in qualitative agreement with AULD and BIRD's Monte-Carlo simulation [3]. No comparison is possible with Sternberg's estimations [2] since they deal with different flow conditions (much lower shock Mach numbers).

The reported method of experiment can, with some modification, be used for investigating the triple point region in the range of parameters which von Neumann's theory fails to describe.

References

1. J. von NEUMANN, Collected works, 6, Pergamon 1963.
2. J. STERNBERG, *Triple, shock wave intersections*, Phys. Fluids., 2, 2, 179–206, 1959.
3. D. J. AULD, G. A. BIRD, *Monte-Carlo simulation of regular and Mach reflection*, AIAA Journal, 15, 15, 638–641, 1977.
4. Z. A. WALENTA, A. S. GMURCZYK, W. W. HARASIMOWICZ, E. M. LEŚKIEWICZ, M. TARCZYŃSKI, J. ORZEŃSKI, K. J. SALGUT, *Rura uderzeniowa ZMCiG*, Prace IPPT, 47, 1976.
5. E. W. HUBBARD, P. C.T. DE BOER, *Flow field behind a shock wave in a low pressure test gas*, Phys. Fluids, 12, 12, 2515–2521, 1969.
6. Z. A. WALENTA, *Wpływ niejednorodności gazu na proces odbicia fali uderzeniowej*, Prace IPPT, 48, 1976.
7. H. OERTEL j. *Berechnungen und Messungen der Dissoziations-relaxation hinter schief reflektierten Stössen in Sauerstoff*, Ph. D. Thesis, Univ. Karlsruhe 1974.
8. H. G. HORNUNG, H. OERTEL, R. J. SANDEMAN, *Transition to Mach reflexion of shock waves in steady and pseudosteady flow with and without relaxation*, J. Fluid Mech., 90, part 3, 541–560, 1979.
9. W. FISZDON, Z. A. WALENTA, A. WORTMAN, *An experimental and theoretical study of the distortion of a travelling shock wave by wall effects*, Arch. Mech., 25, 5, 861–870, 1973.
10. G. BEN-DOR, *Regions and transitions of nonstationary oblique shock-wave diffractions in perfect and imperfect gases*, UTIAS Rep. No 232, 1978.
11. C. K. LAW, *Diffraction of strong shock waves by a sharp compressive corner*, UTIAS Tech. Note No. 150, 1970.
12. L. F. HENDERSON, A. LOZZI, *Experiments on transition of Mach reflexion*, J. Fluid Mech., 68 part 1, 139–155, 1975.

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