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Schock wave reflection close to the leading edge of a wedge

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THE AIM OF THE PRESENT investigation is to show the development of the shock reflection process as soon as a shock wave hits a wedge. To resolve the structure of the shock waves, the experiments were performed under rarefied gas conditions. Because no field method is sufficiently sensitive, a laser differential interferometer was used. Varying the wedge angle, the development of the different types of reflection (regular reflection, Mach reflection) could be observed.

1. Introduction

DUE TO THE GIVEN wedge angle, the incident shock Mach number, and the kind of gas, the shock reflection will either be a regular one or a Mach reflection.

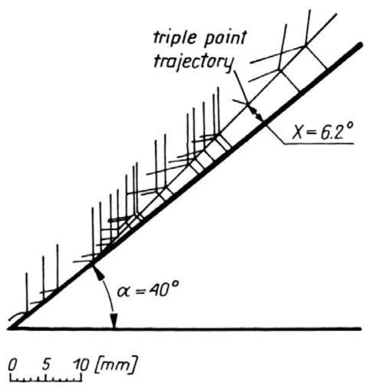

FIG. 1. Delay of the development of the Mach stem. Measurements with double exposure method (SCHMIDT 1983). $M \approx 5$, wedge angle $\alpha = 40$ deg, argon, $p_1 = 266.6$ N/m^2, $\overline{\lambda} = 0.025$ mm. The traces are taken direct from the enlarged negatives.

But close to the leading edge of the wedge, a certain delay in the development of the Mach stem was observed. This phenomenon has been reported by BLEAKNEY and TAUB [1] and later on by WALENTA [2] and by SCHMIDT and WALENTA [3]. Figure 1 shows the results of Schmidt obtained with the double exposure differential interferometer [4] at an initial pressure of $p_1 = 266.6$ N/m^2. It can be seen that the triple point trajectory does not start at the leading edge of the wedge but about 17 mm downstream of it. A model of HORNUNG [5] described this observation simulating the influence of the strong shear layer by a distribution of sinks at the wall. His model agreed with the experimental results.

The main questions at the beginning of the present work have been: "Where does the triple point of a Mach reflection come into existence and how does the triple point trajectory develop?" The resolution of the double exposure pictures was too poor to see the structure of the reflection process and to decide whether it is a transition from regular reflection to Mach reflection or only a Mach reflection. To get more insight into the structure of the reflection process, the experiments have to be performed under rarefied gas conditions.

2. The structure of the reflection process

The measurements are performed in argon with a shock Mach number of 3.8. At rarefied gas conditions (initial pressure $p_1 = 13.33$ N/m^2) the mean free path is large enough ($\overline{\lambda} \approx 0.5$ mm, hard sphere model) to resolve the shock structure (overall shock thickness 8–10 $\overline{\lambda}$). Because no field method of flow motion measurement is sufficiently sensitive, a laser differential interferometer (LDI) was used. The LDI measures the density difference between the two beams of an interferometer, both passing through the flow field. Four interferometers are stacked one upon the other (Fig. 2). So we get with one run four traces at different distances to the wedge surface. The amplified signals (Fig. 3) are stored in four Transient Recorders which are connected to a PC for signal processing. With a stack of four interferometers and four runs at the same position in x-direction, a sufficient vertical distance above the wedge is covered. To match the single

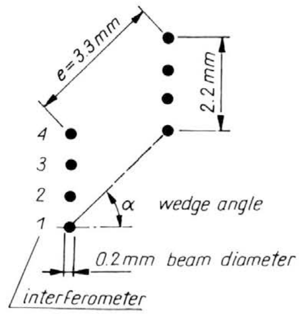

FIG. 2. The dimensions of the four stacked differential interferometers.

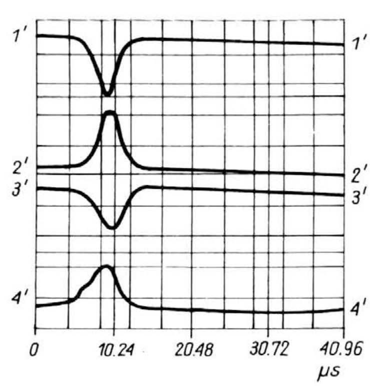

FIG. 3. Typical traces of the four interferometers. Drawn is the voltage over the time.

runs, the last trace of the lower set and the lowest trace of the lifted set have the same distance to the wedge surface.

For a pseudo-steady flow field the signal traces at one position can be summed up with respect to the distance e between the two beams of an interferometer starting in front of the shock wave.

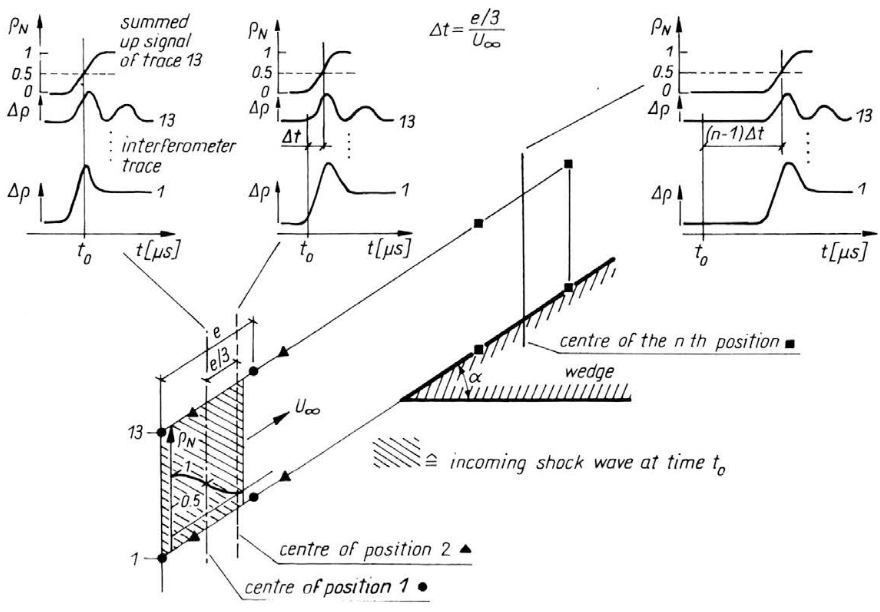

FIG. 4. Procedure to arrange the data set for time t_0.

If the flow field is unsteady, it is necessary to measure in the whole observed region advancing in small steps of 1.1 mm. The data reduction requires a connection between the signal trace and the position where it is recorded. For this connection a characteristic feature of the signals is needed with the same shape at each position and constant speed. The signal of the undisturbed incoming shock wave meets these requirements. This signal is recorded at the greatest distance to the wedge surface. The data reduction starts at position 1 for the time step t_0 with the determination that the centre of the incoming shock wave $\rho_N = 0.5$ coincides with the centre of the first position (Fig. 4). Therefore the signal with the incoming shock wave has to be summed up with the method for pseudo-steady flow. At $\rho_N = 0.5$ for the time step t_0 the values $\Delta\rho$ of all traces can be stored. At the next position the procedure is just the same, but we have to regard the time the incoming shock wave needs to reach the centre of position 2. With this time difference Δt in negative direction on the time scale we have the time t_0 for position 2 and the values $\Delta\rho$ can be stored. With respect to the n-th position the time difference is $(n-1)\Delta t$. Similar to the pseudo-steady method, the density differences for each interferometer are summed up starting in front of the shock wave (n-th position). For the following time steps an arbitrary difference δt in positive direction of the time scale is used. Again the values are summed up. Finally a matrix with the density ρ_N at each grid point is given for each time step and the isopycnics can be plotted.

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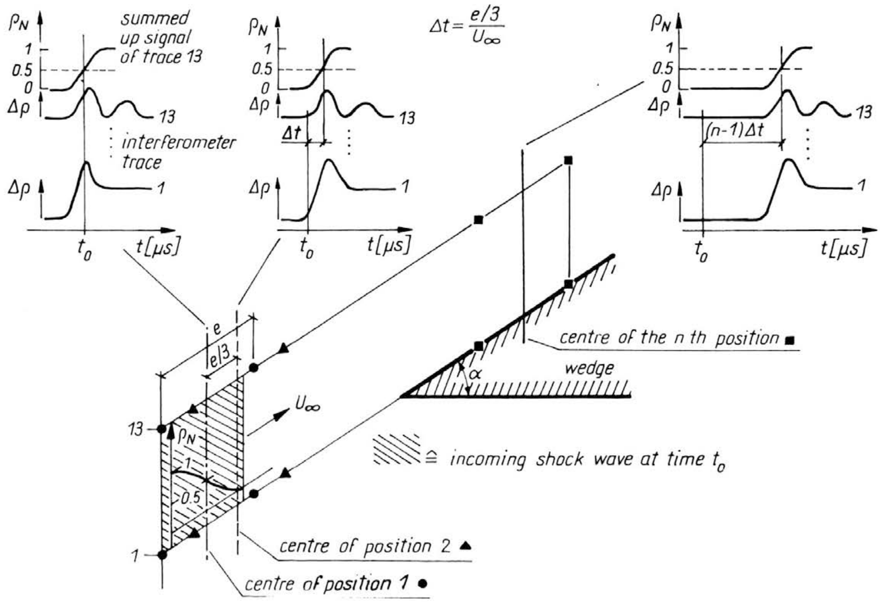

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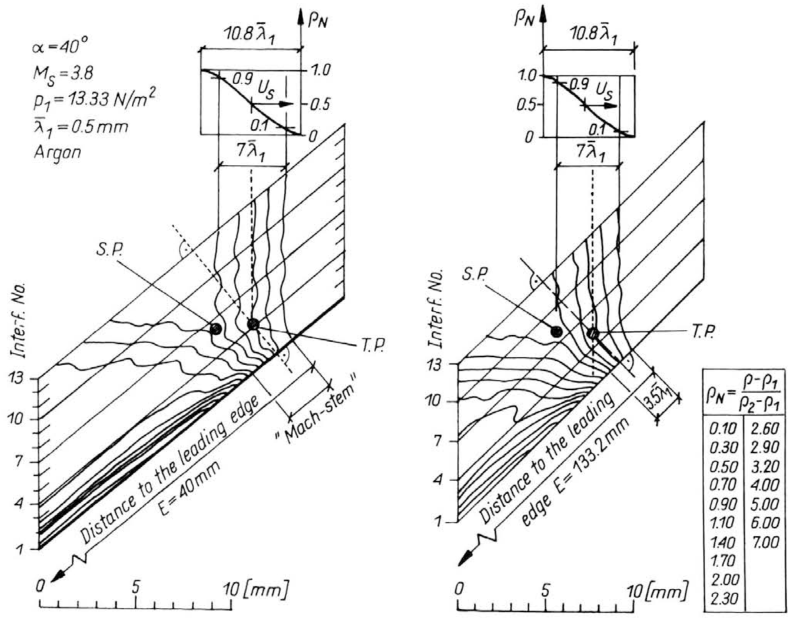


FIG. 6. Geometrical construction of the triple point location.

with α = 30 deg, 40 den and 45 deg. For the wedges with α = 20 deg and 60 deg no trace displays a hump. The separation is manifested in signs that are not so obvious.

Figure 7 shows data for the location of the triple point, the separation point and their trajectories. The trajectories of both points are for a relative long distance parallel to the wedge surface. The Mach steam is barely visible.

As soon as the incoming shock wave touches the leading edge of the wedge, it takes about the time the shock needs to move about half of its thickness on the wedge for the flow to establish. For the wedge angles α = 20, deg, 30 deg, 40 deg and 45 deg the Mach stem grows very fast to a length of about 1 mm. Then this length keeps constant for some distance from the leading edge of the wedge. Here the influence of the shear layer suction is dominant and the Mach stem seems to be a part of the shear layer. For the growing of the Mach stem, the mass flow through the Mach stem has to be larger than the amount of gas that is sucked into the shear layer. The type of reflection is definitely a type of Mach reflection. This part could not be resolved in the double exposure photographs. The reflection looked like a regular one in a region, where the Mach stem is too short to get visible. Only to the wedge angle α = 60 deg no sign of a TP or a short Mach stem is visible. For this angle the reflection is regular for any shock Mach number. The investigation of all the other wedge angles show that the TP can be located already very close to the leading edge, if the final form of reflection is a Mach type one.

3. Comparison of low density structure results with continuum ones

Figure 8 shows the comparison of the low density structure results with continuum ones. For both pictures the same length scale was used. The mean free path of the low

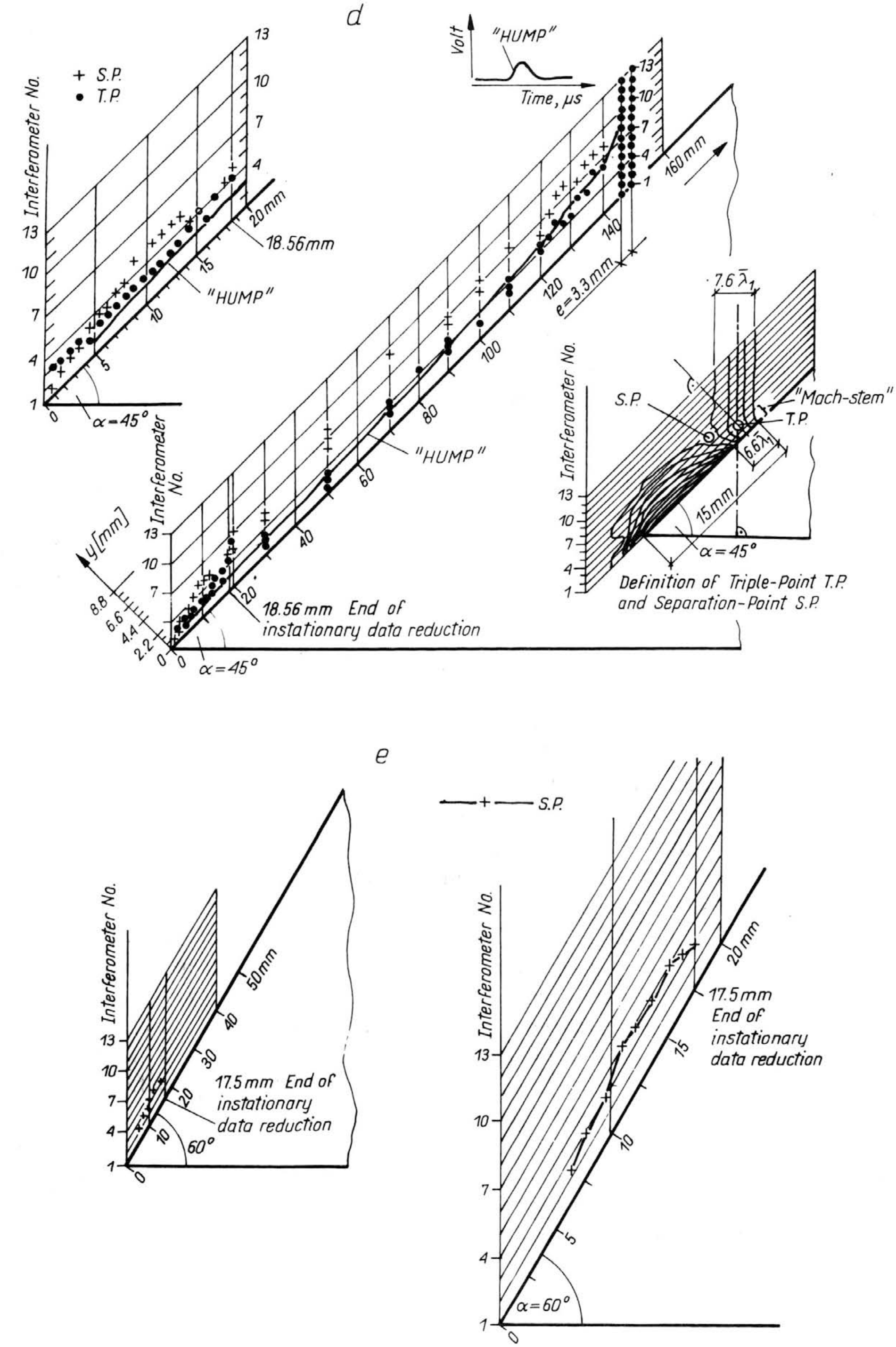
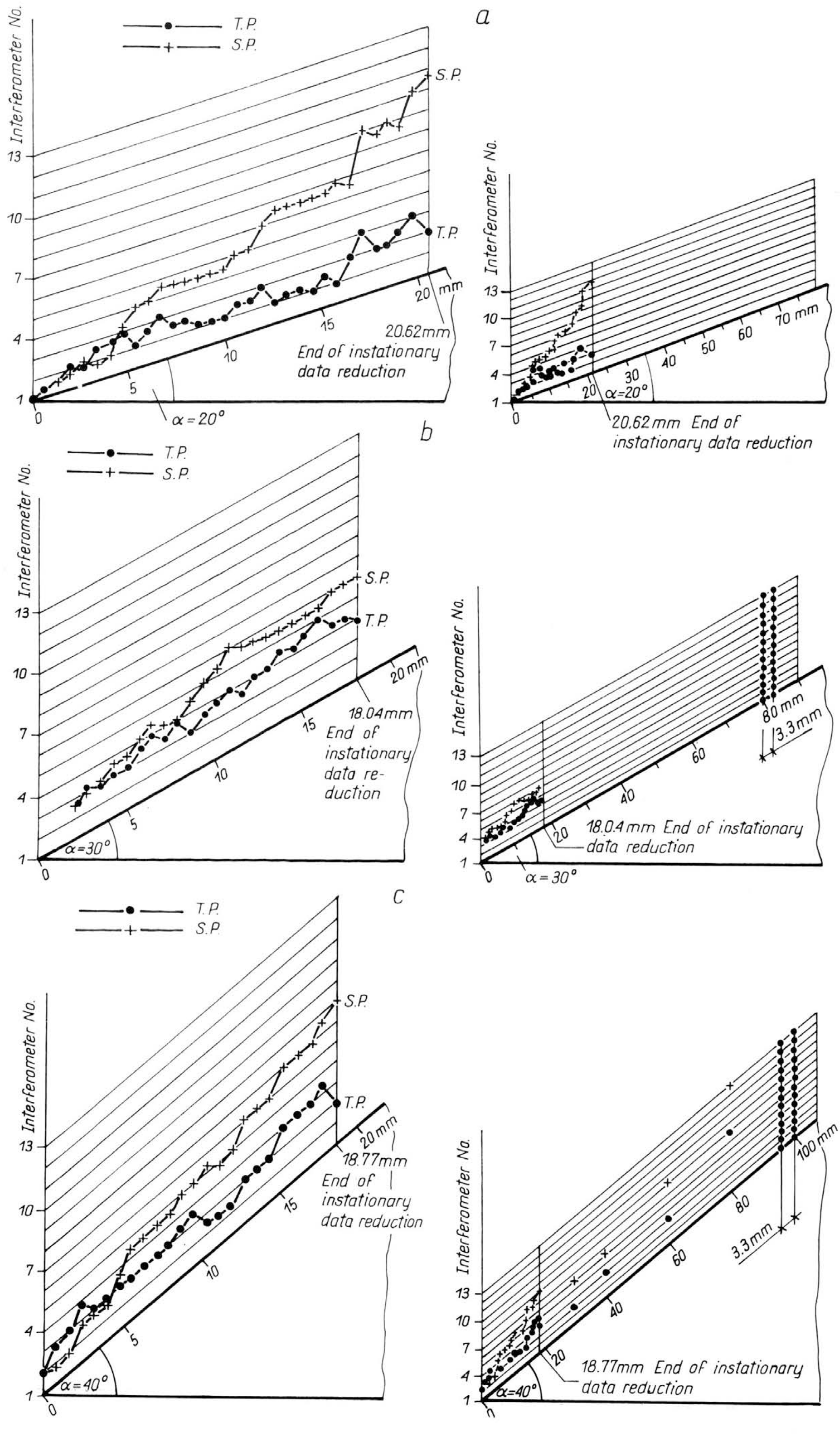


FIG. 7. Trajectories of the triple point and the separation point. a) $\alpha = 20$ deg, b) $\alpha = 30$ deg, c) $\alpha = 40$ deg, d) $\alpha = 45$ deg, e) $\alpha = 60$ deg.


a
Interferometer No.
T.P.
S.P.
20.62mm
End of instationary data reduction
α = 20°
mm
20.62 mm End of instationary data reduction
b
18.04mm
End of instationary data reduction
α=30°
18.0.4 mm End of instationary data reduction
3.3 mm
80 mm
c
18.77mm
End of instationary data reduction
α=40°
18.77mm End of instationary data reduction
3.3 mm
100 mm
20 mm

density results is 20 times larger. It can be seen that the shock thickness grows with the mean free path (the shock thickness in the double exposure pictures is larger due to the exposure time of the sparks), whereas the shock reflection is the same. Thus, the mean free path cannot be a scaling factor for the shock reflection.

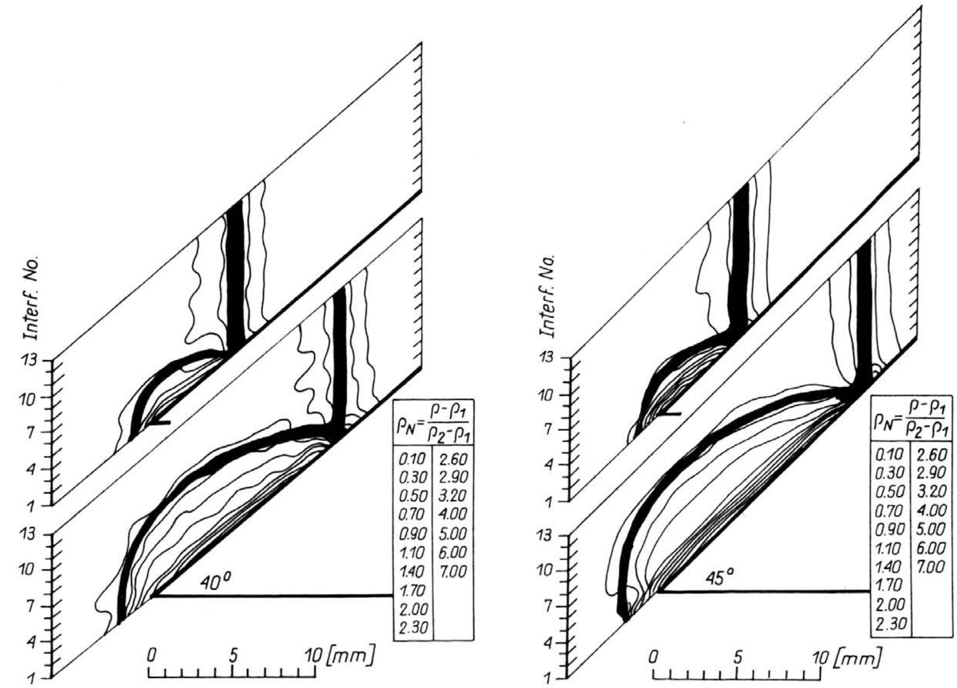


FIG. 8. Comparison of continuum results (double exposure data) with structure results (low density data).

4. Comparison of the results with those of other scientists

The measurements done by WALENTA [6] allow the remark that the flow pattern seems to be the same. But Mach number, wedge angle, kind of gas and probing device (electron beam densitometer) are different.

The numerical calculations of SERIKOV and YANITSKIY [7] can be compared directly with our results, because the input data are the same. The global agreement is good (Fig. 9). Close to the wedge surface, however, there are remarkable differences in the pattern of the lines of constant density. The accommodation coefficient is of large influence on the behaviour of the flow close to a solid wall. For the calculations shown in Fig. 9 an accommodation coefficient of $\alpha = 1.0$ (diffuse reflection) was used. Calculations with an accommodation coefficient equal to 0 (specular reflection) are of no use for a comparison. The shear layer is not produced, which is of greatest influence on the flow under investigation. But for $\alpha = 1.0$, being called: "full accommodation", the interaction between the wall and the flow is too strong. An accommodation coefficient

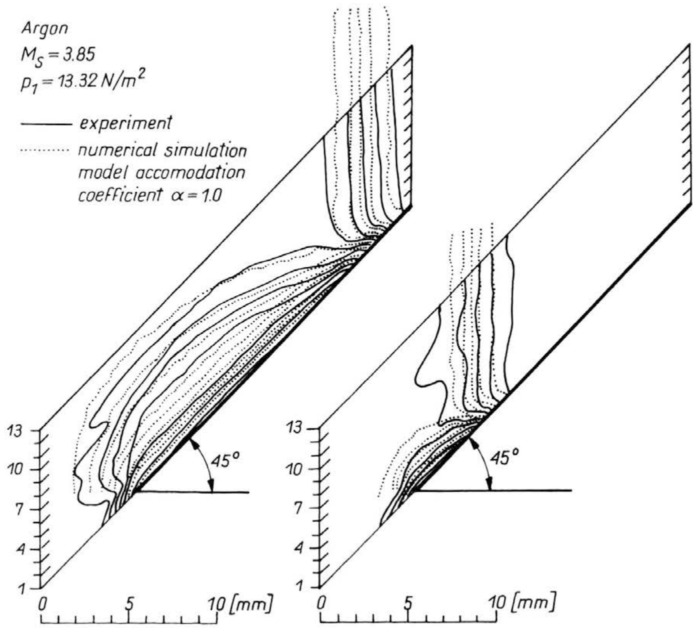


FIG. 9. Numerical results [7] compared with experimental data at two places.

between 0.5 and 1.0 should give a better fit to the experimental data. In general it can be said that the simple model with the accommodation coefficient is the only one that is applicable.

5. Conclusions

The object of interest is the reflection process of a plane shock wave with an inclined plane surface. To see the structure of the developing reflection close to the leading edge of the wedge the pressure of the test gas argon was set on $p_1 = 13.33\ N/m^2$. The structure became visible and the interaction process could be observed. Because of the numbers of runs being necessary for one set of parameters, only the wedge angle has been changed (α = 20 deg, 30 deg, 40 deg, 45 deg, 60 deg). For the wedge angles smaller than 60 deg and a Mach number of 3.8, the type of reflection is always a Mach reflection [3]. Our structure results show that the type of reflection can be identified already very close to the leading edge. In the case of Mach reflection the triple point can be found by a geometric construction. The triple point appears immediately behind the leading edge and the triple point trajectory remains for a long distance adjacent to the wedge surface.

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References

1. W. BLEAKNEY and A. H. TAUB, *Interaction of shock waves*, Rev. Mod. Phys., **21**, pp. 584, 1949.
2. Z. A. WALENTA, *Formation of the Mach-type reflection of shock waves*, Arch. Mech., **35**, pp. 187, 1983.
3. B. SCHMIDT and Z. A. WALENTA, *Development of a quasi-stationary Mach reflection of shocks, influence of the degree of rarefaction upon transition from regular to Mach reflection*, 16th Biennial Fluid Dynamics Symp., Spała, Poland, 1983.
4. H. OERTEL sen. and H. OERTEL jr., *Optische Stroemungsmesstechnik*, Karlsruhe Brann, 1989.
5. H. HORNUNG, *Regular and Mach reflection of shock waves,* Ann. Ref. Fluid Mech., **18**, pp. 33, 1986.
6. Z. A. WALENTA, Private communication, 1990/1991.
7. V. YANITSKIY and V. SERIKOV, Private communication, 1990/1991.
8. G. BEN-DOOR and I. I. GLASS, *Domains and boundaries of non-stationary oblique shock wave reflections. 2. Monatomic gas*, JFM, **39**, pp. 735, 1980.

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