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SUMMARY

It is shown that the non-steady expansion which arises at the diaphragm in a shock tube may be replaced by a steady expansion if a nozzle is fitted in the tube near the diaphragm. The method is useful in eliminating the pressure rise at the end of the tube associated with the arrival of the tail of the unsteady expansion but the increased pressure ratio across the diaphragm which is required may be a disadvantage.

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1. Introduction/

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1. Introduction

The wave diagram of a simple shock tube with closed ends is shown in Fig.1 together with the pressure record which would be expected. The primary shock is reflected from the end wall and meets the contact surface at A. A shock is transmitted through the contact surface and either a shock or an expansion may be reflected from it. For hydrogen-air operation the nature of the reflected wave has been discussed in the literature[1-3], and it has been shown that at shock Mach numbers U_{S1}/a_1 greater than 6.02 the first reflected disturbance is a shock wave and that subsequent multiple reflections result in a slowly increasing pressure. At shock Mach numbers less than 6.02 the first reflected disturbance is an expansion although subsequent reflections may be shock waves. The pressure at the end of the tube (for $M_{S1} > 6.02$) is increased when the tail of the unsteady expansion arrives after refraction through the contact surface. It continues to rise until the head of the expansion, which has been reflected from the closed end of the driver tube, reaches the end of the driven tube; the pressure then falls rapidly.

In some applications, particularly in the case of the shock tunnel, the lengths of the driver and driven tube, L' and L, will be chosen to give the maximum time t_3 between the arrival of the shock and the reflected head.

At low shock Mach numbers the reflected head of the expansion reaches the end of the driven tube before the tail in a tube which has been designed for optimum operation at the higher shock Mach numbers, say 6 and greater, and thus there is no need to alter this state of affairs. In an optimally designed tube the reflected head and the tail arrive simultaneously at the end of the driven tube[3], but since this condition is satisfied for only one shock Mach number, for a given ratio of L'/L, Fig.1, the tube is generally operated in the non-optimum condition and the tail may arrive before the reflected head. It is desirable to maintain as constant a pressure as possible at the nozzle entrance of a shock tunnel, and thus any means of alleviating the pressure rise due to the tail of the expansion merits attention.

2. Steady Expansion from Diaphragm

The possibility of eliminating the unsteady expansion at the diaphragm was first suggested by Wittliff et al[1]. The wave diagram for such a shock tube is shown in Fig.2. A nozzle designed with an area ratio appropriate to the flow Mach number M_3 behind the contact surface is inserted near the diaphragm. Ideally the diaphragm should be located at the nozzle throat as shown, but difficulties associated with the rupture of the diaphragm necessitate an up- or downstream location, Fig.6. The pressure is thus constant (at a value $p_3 = p_2$) in the region between the contact surface and the diaphragm. The reflected shock after passing through the contact surface is partially reflected from the nozzle, and the termination of quasi-steady pressure at the end of the driven tube is determined by the arrival of this disturbance, or the reflected head of the expansion depending on tube geometry.

2.1 The nozzle area ratio

The flow Mach number, M_3, behind the contact surface is given by the expression,

$$M_3 = \frac{u_3}{a_3} = \frac{1}{\beta_4 \gamma_4}\left[\left(\frac{p_{21}}{p_{41}}\right)^{-\beta_4} - 1\right], \qquad \ldots(1)$$

which/

which is derived in several reports, for instance[4], and which is plotted as a function of M_{S1} in Fig.3. The required nozzle area ratio A/A^* may thus be selected for each shock Mach number from tables such as those of Ref.5 which are also plotted in Fig.3.

2.2 Experiments in a 2in. diameter shock tube

The dimensions of the shock tube in which the experiments were carried out are shown in Fig.4. Curves, showing the computed times of arrival of the various disturbances at the end of the tube are shown in Fig.5. The values for the tail and reflected head were computed on the basis of simple theory neglecting viscous and real gas effects. A comparison between the inviscid calculation for the contact surface and a viscous solution[6] is also shown. The viscous theory accounts for the loss of test gas to the boundary layer, and experimentally determined contact surface positions which are in good agreement with this theory are shown in Fig.5. Also plotted are the observed times of arrival of the reflected head of the expansion, and the agreement with perfect gas theory is reasonable except at low shock Mach numbers. There are low-temperature real gas effects present in the reflection of the head of the expansion, but apparently these do not seriously affect the times measured.

It will be seen from Fig.5 that in the 2 in. diameter shock tube the tail of the unsteady expansion arrives before the reflected head only for shock Mach numbers greater than 8, and this figure sets a lower limit to the experiments in the tube with its present geometry.

2.3 Steady expansion at $M_{S1} = 9.75$

At a shock Mach number of 9.75 the flow Mach number behind the contact region, M_3, is 3.65 and the area ratio required for the diaphragm nozzle is 7.802. A convergent divergent nozzle generated by circular arcs was fitted to the high pressure side of the main diaphragm as shown in Fig.6. It was found that if the nozzle was placed downstream of the diaphragm the petals partially blocked the throat whose diameter was 0.672 in.

A pressure transducer* was mounted in the closed end of the driven tube and a record such as that in Fig.7 obtained with no diaphragm nozzle fitted. The position of the reflected head is clearly defined although the ratio of the equilibrium pressure** to the pressure after the first reflection $p_{e5} = 2.21$ is somewhat lower than that predicted by simple theory[3], but in general agreement with experiments at lower shock Mach numbers. Tests in a 3 in. diameter shock tunnel indicated that the equilibrium pressure was higher than predicted, and there is apparently an effect of tube geometry. For this reason it is not suggested that the predicted position of the tail of the expansion is seriously in error.

The nozzle was then fitted to the high pressure section of the tube and pressure records such as that in Figs.8(a), (b) and (c)

were/

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*SLM type PZ.6 manufactured by the Swiss Locomotive Works, Winterthur.

**Defined in Ref.3 as the pressure at the arrival of the tail of the expansion, after multiple reflection of the incident shock between wall and contact surface.

were obtained at shock Mach numbers of 9.29, 9.79 and 10.3 respectively. In the case of Fig.8(b), $M_3 = 3.69$, the closest that was achieved to the desired value of 3.65. It will be seen that the pressure does not in fact continue to rise after the time at which the tail would normally have arrived. The pressure rises less uniformly in the initial stages than was the case without the nozzle, but the final value of p_{e5} is 2.53, approximately the same as that obtained without the nozzle. The signal continues to fluctuate until the arrival of the reflected head of the expansion causes a sudden fall in pressure. The records at shock Mach numbers of 10.3 and 9.29 are smoother than that at 9.79, but at present this is unexplained.

2.4 Steady expansion at $M_{S1} = 8.8$

It will be seen from Fig.5 that, at this shock Mach number, the tail of the unsteady expansion would be expected to arrive 390 microseconds before the reflected head. The predicted location of the tail on the pressure record in the absence of a nozzle is shown in Fig.9, and the effect of adding a nozzle is shown in Figs.10(a) and (b) for shock Mach numbers of 8.73 and 8.98 respectively. There is very little effect on the pressure due to the nozzle in this case, possibly due to there being less time for the pressure to rise between tail and reflected head than in the previous cases.

The pressure ratio p_{RH}/p_e with and without the nozzle is plotted in Fig.11 for the tests at shock Mach numbers of 8.5 to 10.3. The addition of the nozzle is seen on the whole to maintain the pressure more nearly constant although there is no appreciable improvement below $M_{S1} = 9$.

3. Diaphragm Pressure Ratio

One of the disadvantages of using the diaphragm nozzle appears to be the increased pressure ratio required to produce the same shock velocity with the nozzle in place. In Fig.12 the theoretical ratio p_{41} is shown together with measured values from the present and previous experiments without a nozzle in the high pressure section. Also shown are the values of p_{41} required with the nozzles in the high pressure chamber for both area ratios. The increase in p_{41} is approximately 3.5 times over the range of shock Mach numbers from 8 to 10, and this might prove a difficulty in practice where already high pressures are employed in the driver section.

4. Conclusion

From the few measurements made, it may be concluded that the placing of a convergent-divergent nozzle at the diaphragm station does reduce the rise in pressure which would normally occur through the tail of an unsteady expansion. It is thus concluded that a steady expansion is in fact occurring but that the initial pressure ratio required for a givenshock Mach number is about 3.5 times that which would be required without a nozzle.

Acknowledgements

Mr. K. Moreton performed the experiments and Miss M. Healey assisted with the preparation of the report.

List of Symbols

M_S = shock Mach number

M_{S1} = incident shock Mach number

$$= \frac{\text{shock velocity}}{a_1}$$

a = sound speed

M = flow Mach number

β = $\gamma-1/2\gamma$

p_{ab} = p_a/p_b, pressure ratio

p_{RH} = pressure at arrival of reflected head of expansion

subscripts 1, 2, 3, 4 properties of region (1), see Fig.1.

References

No.	Author(s)	Title, etc.
1	C. E. Wittliff, M. R. Wilson and A. Hertzberg	The tailored-interface hypersonic shock tunnel. J. Aero. Sci. Vol.26, No.4. April, 1959.
2	A. Hertzberg, H. S. Glick, W. E. Smith and W. Squire	Modifications of the shock tube for the generation of hypersonic flow. AEDC-TN-55-15. March, 1955.
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4	I. I. Glass, W. Martin and G. N. Patterson	A theoretical and experimental study of the shock tube. U.T.I.A. Report No.2, 1953.
5	Ames Research Staff	Equations, tables and charts for compressible flow. N.A.C.A. Report No.1135, 1953.
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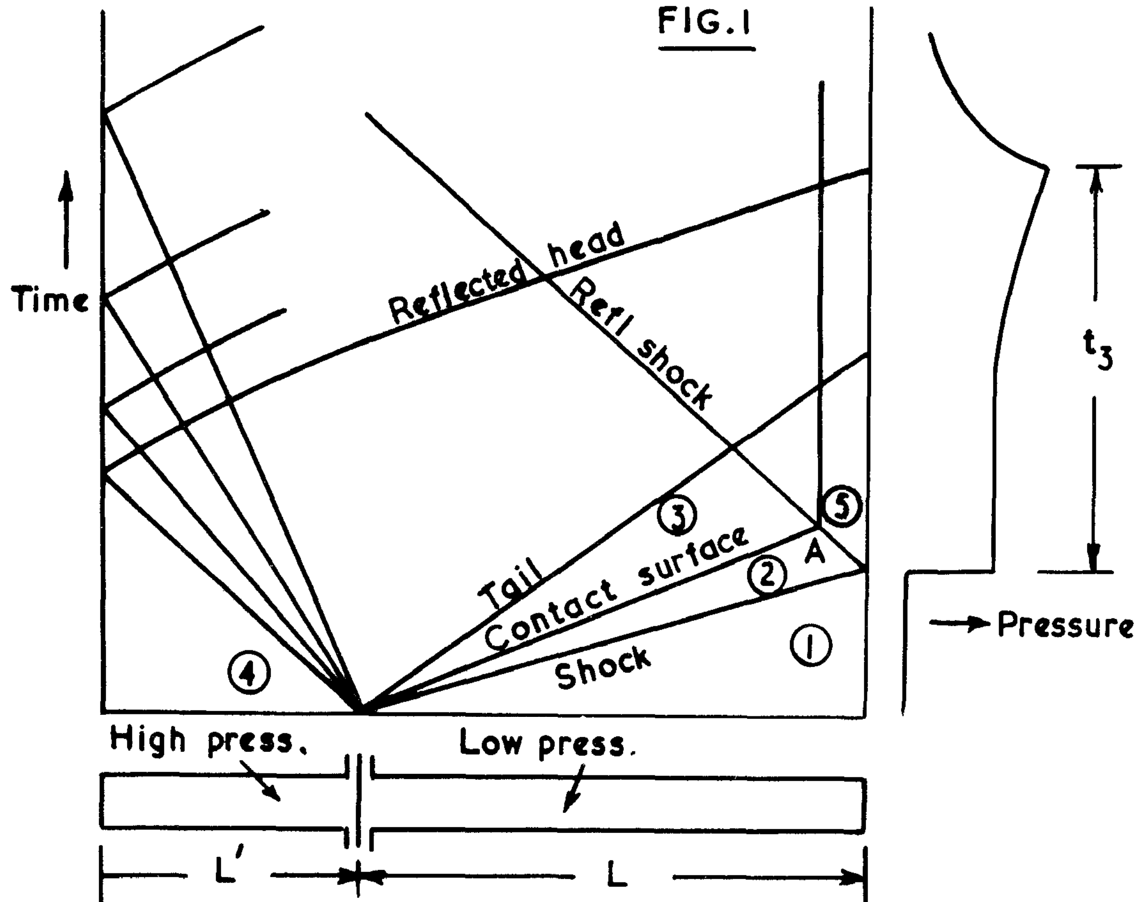
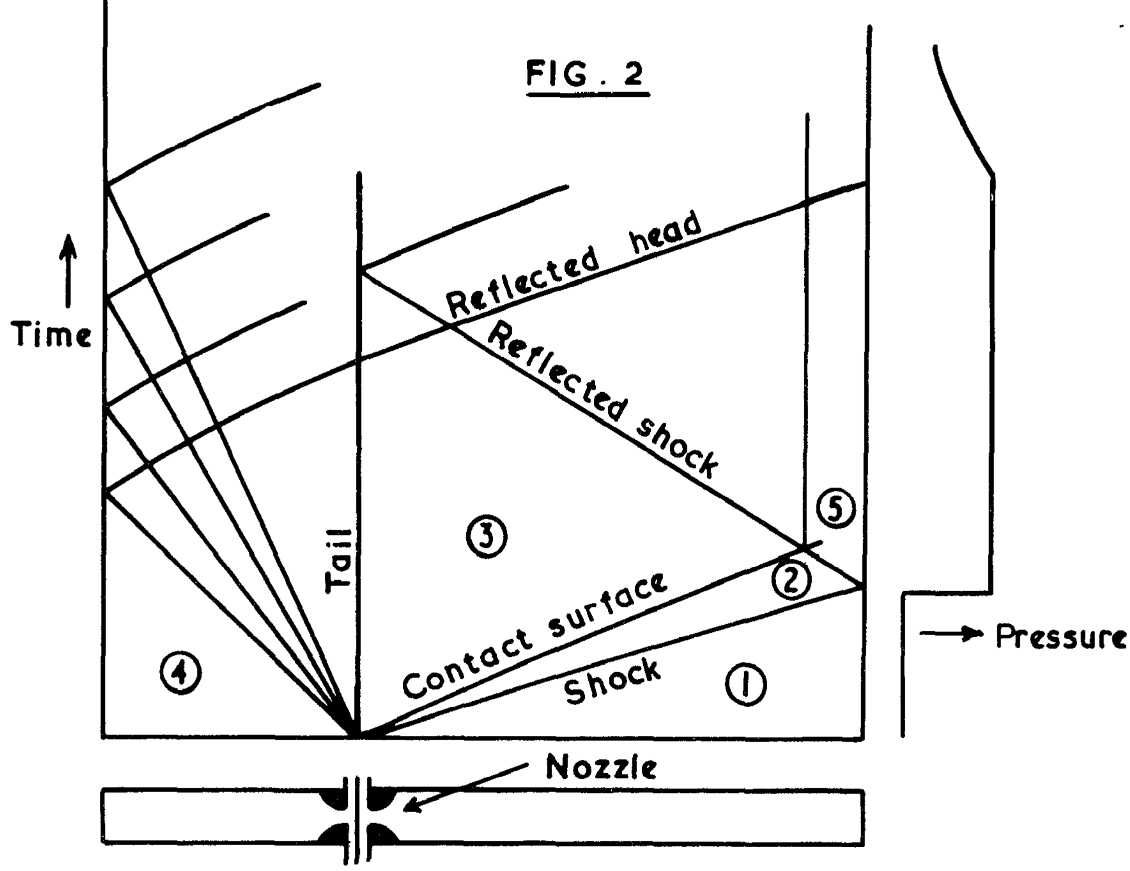
FIGS. 1 & 2

FIG. 1



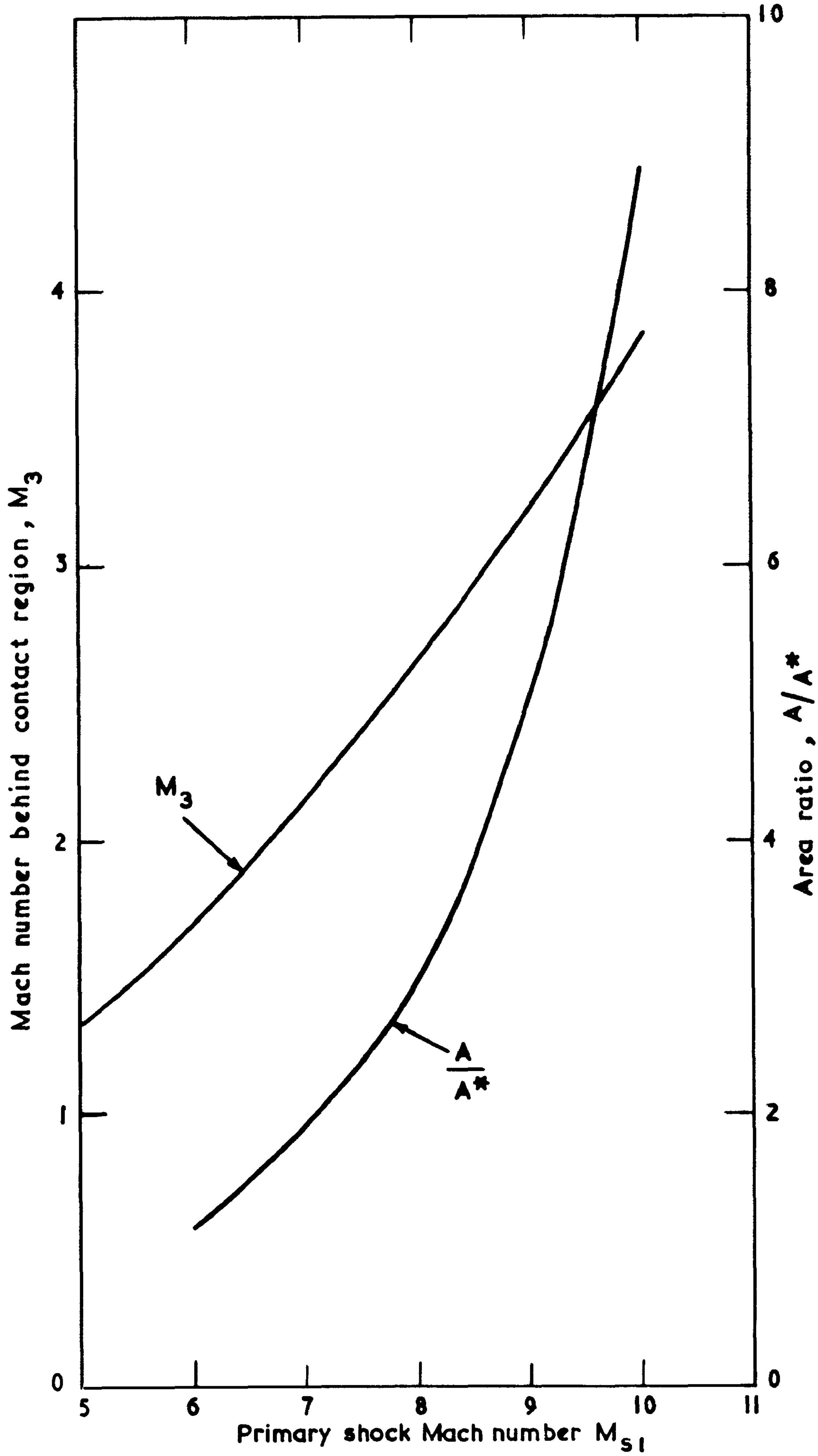
Wave diagram of shock tube with unsteady expansion from diaphragm. Shown for $M_s = 6$ condition.

FIG. 2



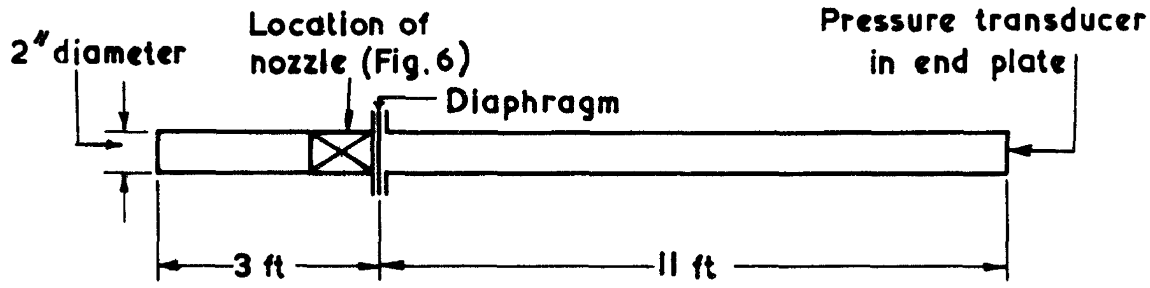
Wave diagram of shock tube with steady expansion from diaphragm. Shown for $M_s = 6$ condition.

FIG. 3



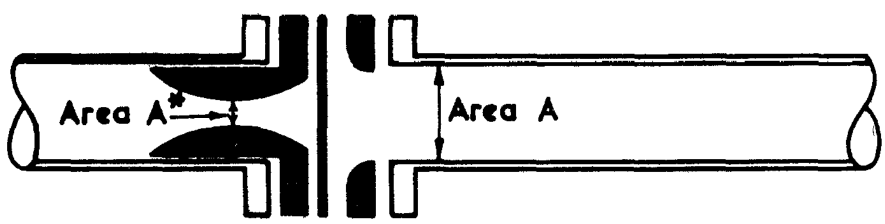
Flow Mach number behind contact region and area ratio of nozzle required.

FIG. 4.



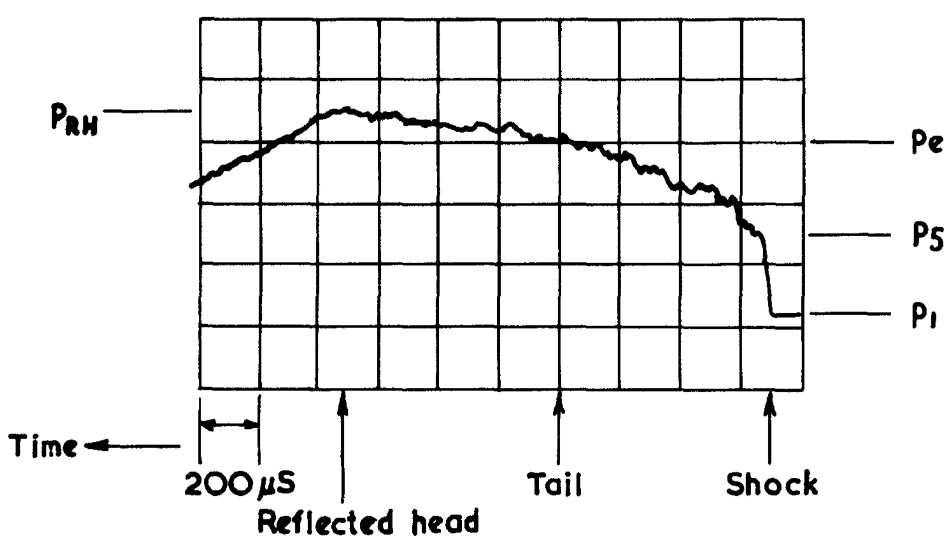
Dimensions of shock tube used in experiments

FIG. 6



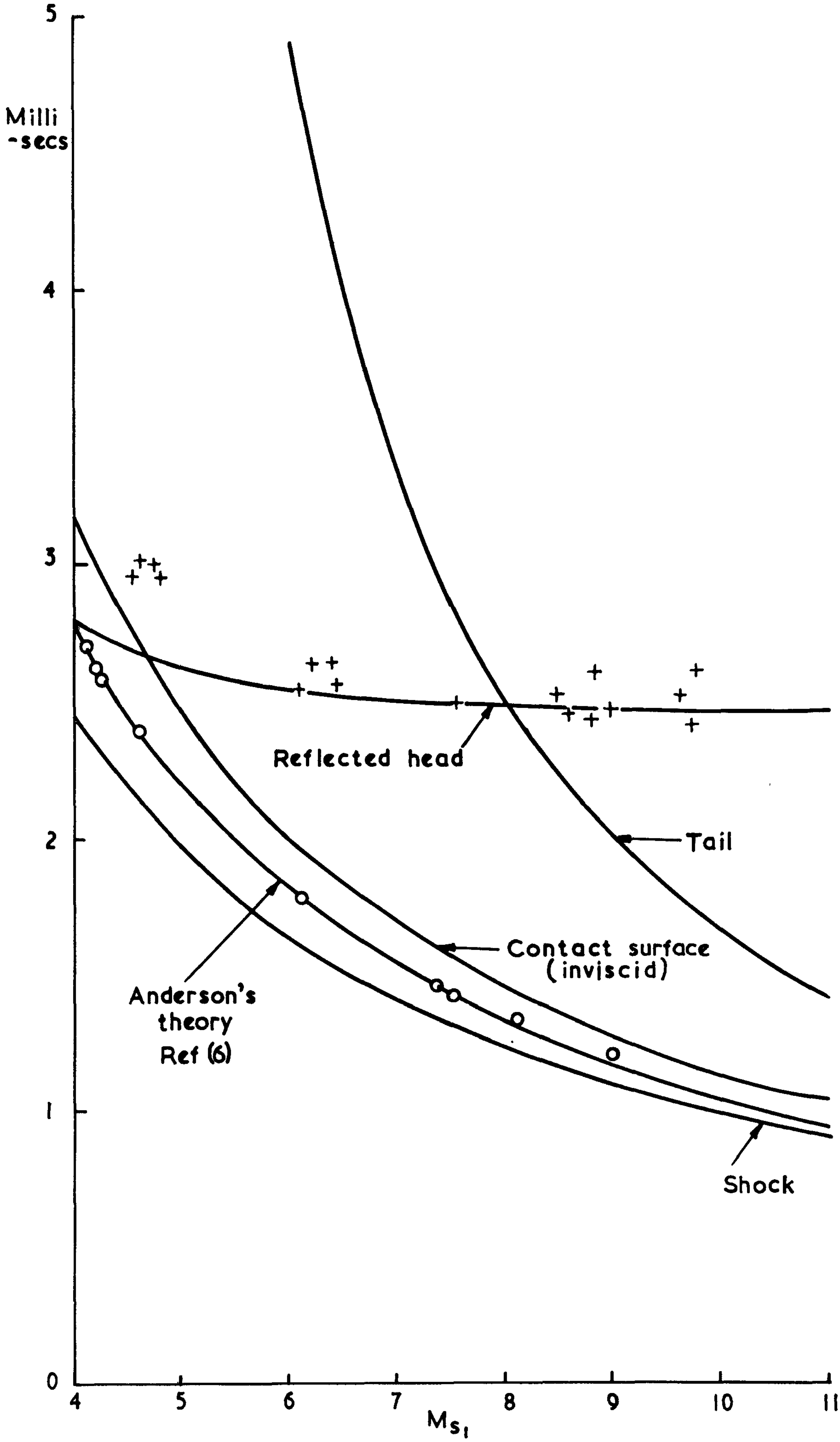
Arrangement of nozzle, diaphragm and diaphragm clamping plate

FIG. 7



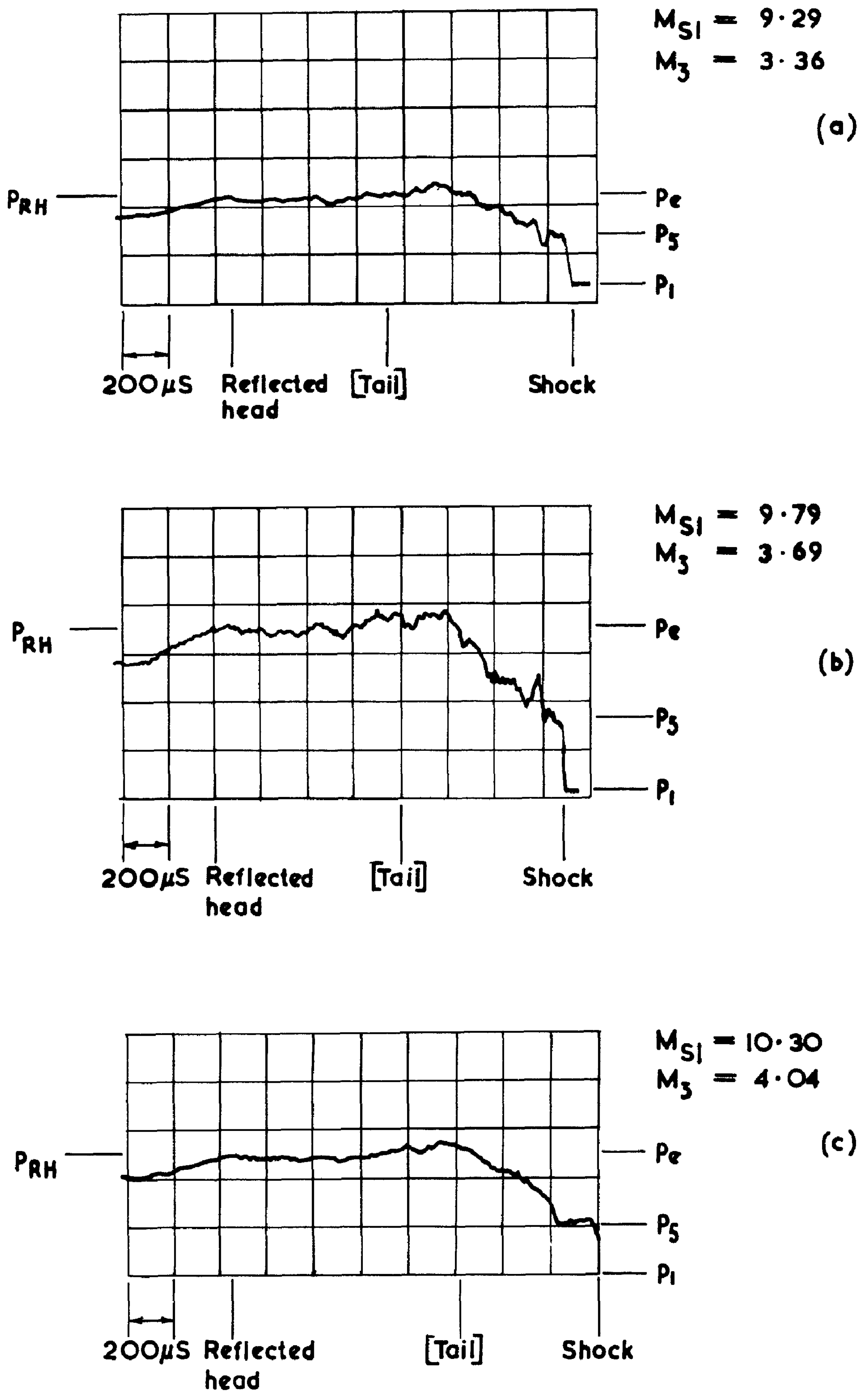
Pressure record without nozzle. $M_s = 9{\cdot}70$. $p_1 = 10$ mm Hg.

FIG. 5.



Time (after rupture of diaphragm) of arrival of shock, contact surface, tail and reflected head at the end of the shock tube.

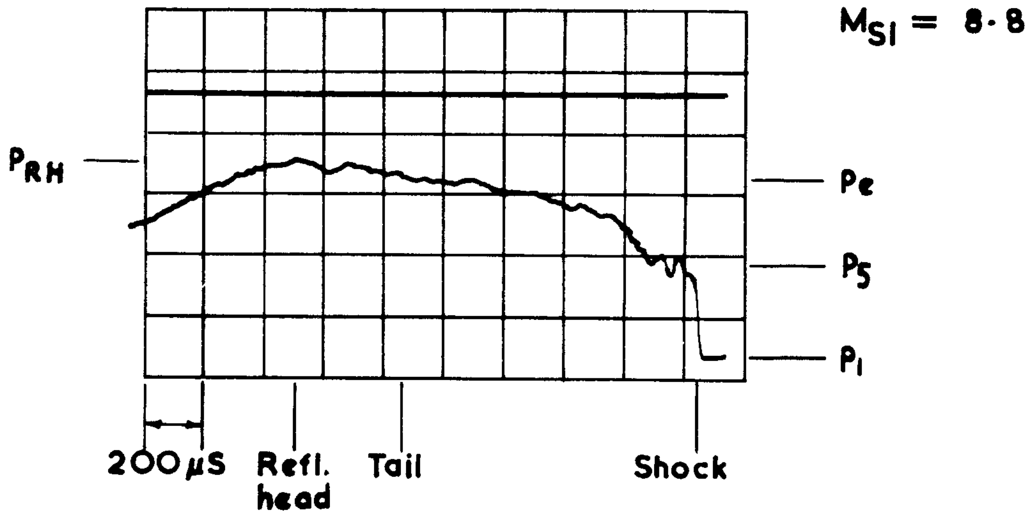
FIG. 8



Pressure records with nozzle designed for $M_{SI} = 9 \cdot 75$, $M_3 = 3 \cdot 65$

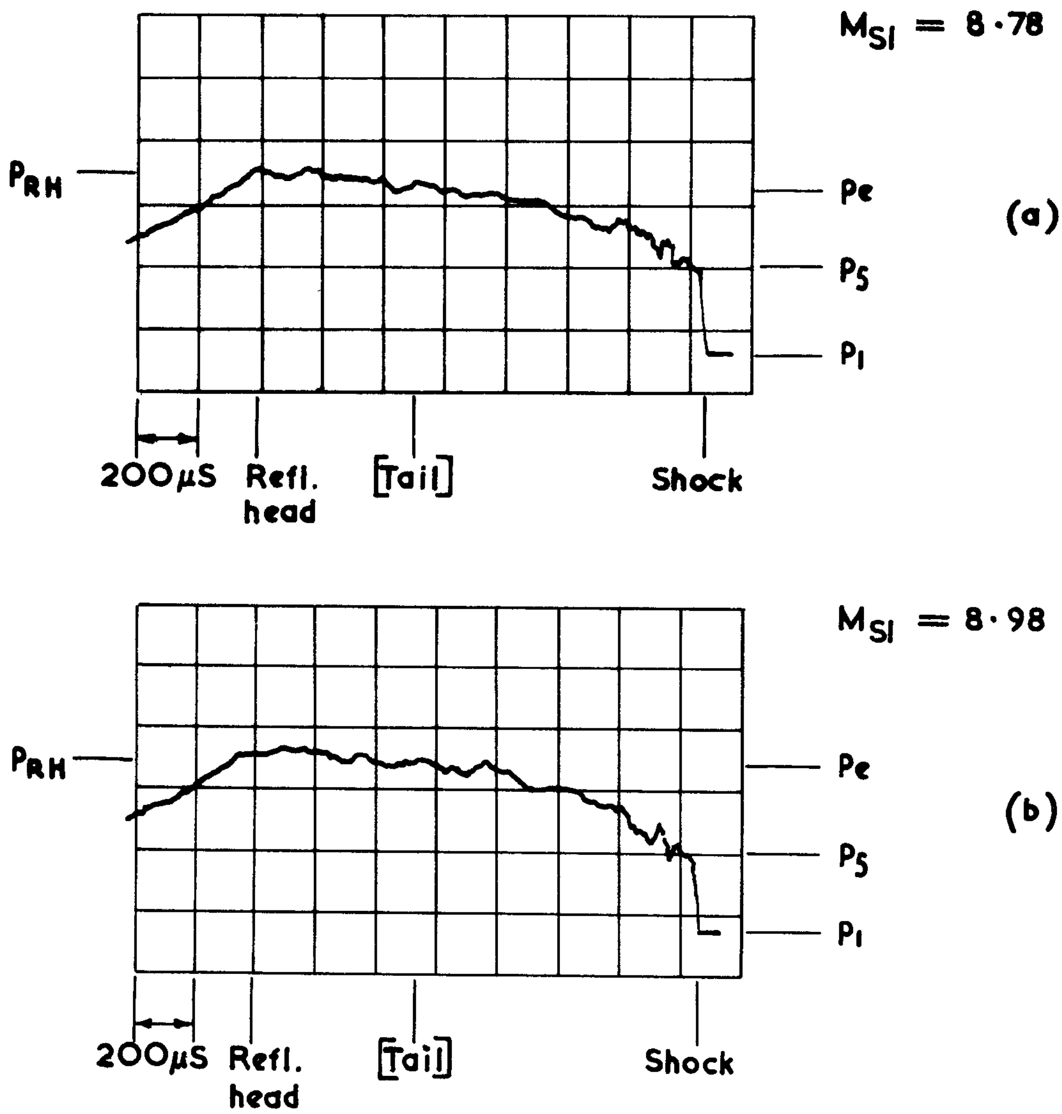
FIGS. 9 & 10

FIG. 9



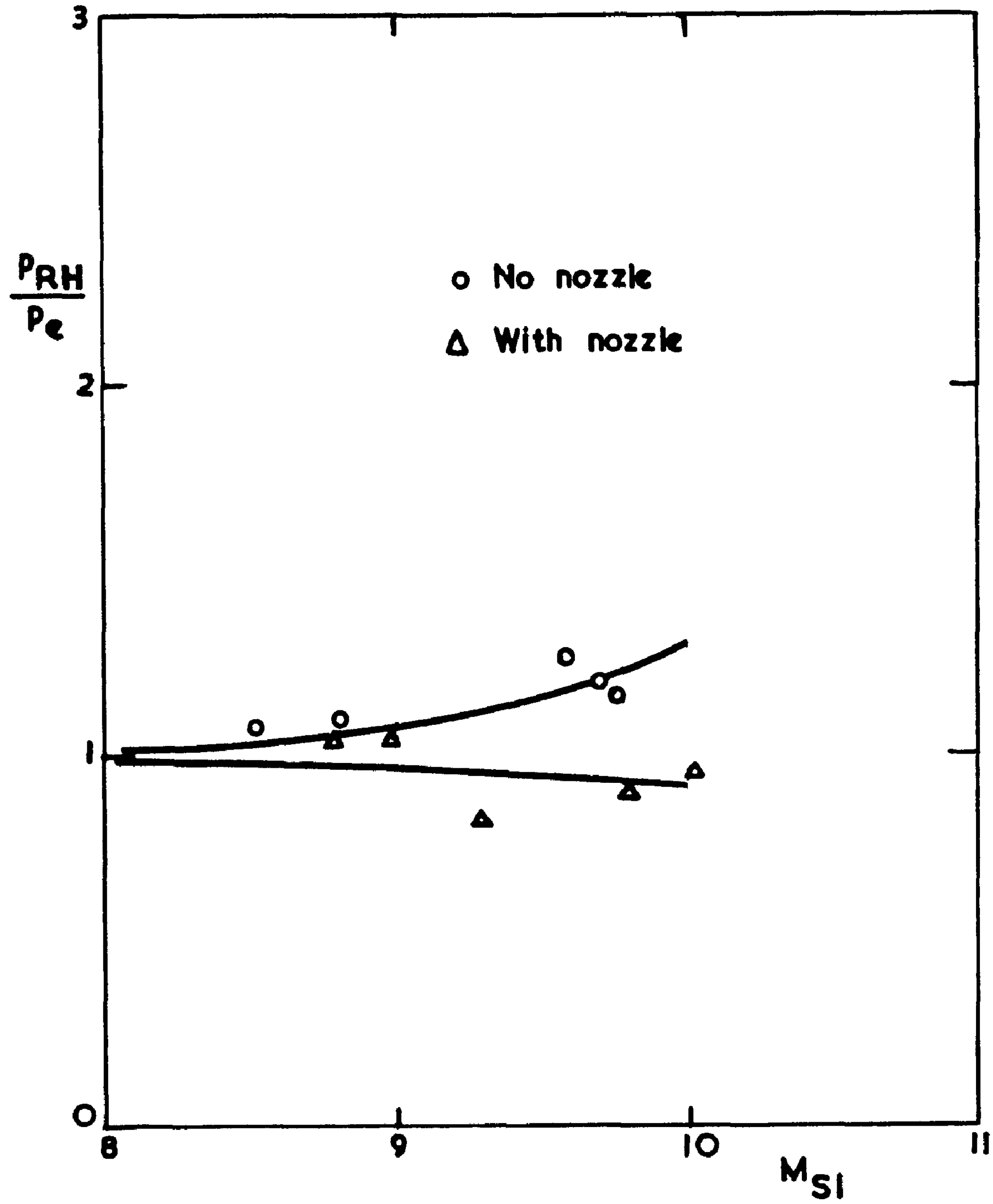
Pressure record without nozzle

FIG. 10



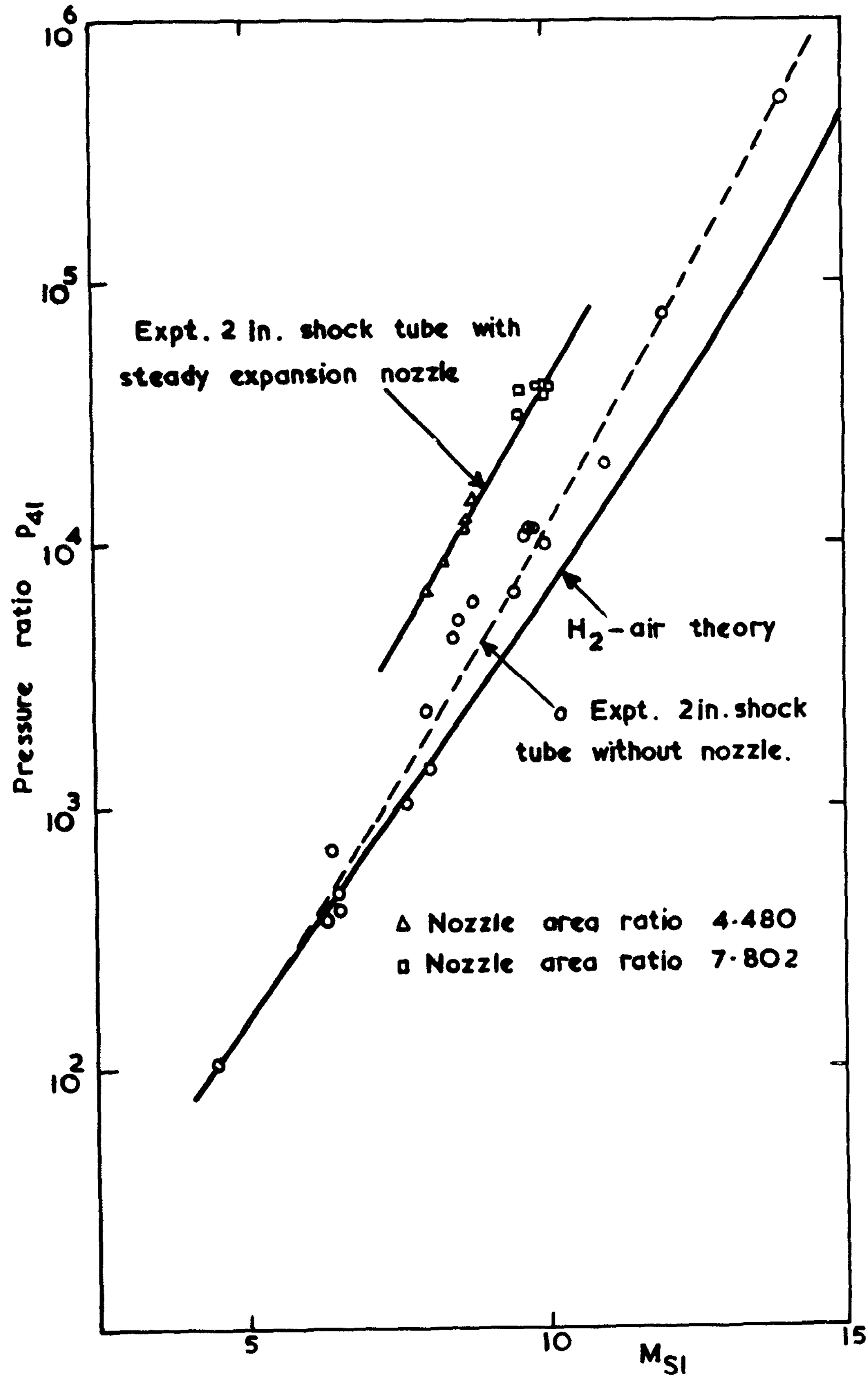
Pressure records with nozzle designed for $M_{S1} = 8 \cdot 8$, $M_3 = 3 \cdot 06$

FIG. 11.



The variation of pressure between the tail and the reflected head of the expansion with and without nozzle

FIG.12.



Pressure ratio p_{41} with and without nozzle

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