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On the Interaction of the Transmitted Shock with the Boundary Layer in a Shock Tube Using Argon as a Test Gas

By

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On the Interaction of the Transmitted Shock with the Boundary Layer in a Shock Tube using Argon as Test Gas

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SUMMARY

It has been suggested in a previous paper[4] that cooling of the hot gas in the region between the reflected shock and the end plate in a shock tube may result from the bifurcation of the transmitted shock. The reflected shock is the reflection of the primary shock at the end plate and the transmitted shock refers to the shock transmitted as a result of the interaction between the contact surface and this reflected shock. Previous work by Mark[6] and others[7] has shown that where argon is the test gas no bifurcation should occur as a result of the interaction between the reflected shock with the boundary layer for primary shock Mach numbers in excess of 3. In this paper it is shown that theory predicts bifurcation of the transmitted shock for primary shock Mach numbers in excess of 3 and some supporting experimental evidence using helium as driver and argon as test gas is presented. The relevance of this investigation to the problem of the cooling of the hot gas produced near the end plate by the reflected shock is discussed and some further experimental work suggested.

Replaces N.P.L. Aero Note 1032 - A.R.C.27 221.

CONTENTS

NOMENCLATURE

a	Velocity of Sound
A_{ij}	$\frac{a_i}{a_j}$
L	Shock tube driven length
M	Mach number $= \frac{u}{a}$
M_1	Primary shock Mach number
p	pressure
P_{ij}	$\frac{p_i}{p_j}$
T	Temperature
T_{ij}	$\frac{T_i}{T_j}$
u	Velocity
U_{ij}	$\frac{u_i}{a_j}$
x	Distance of reflected shock and contact surface interaction from end plate
α_i	$\frac{\gamma_i+1}{\gamma_i-1}$ where $\gamma = \frac{C_p}{C_v}$ - specific heat ratio
β_i	$\frac{\gamma_i-1}{2\gamma_i}$
δ_i	$\sqrt{\frac{2}{\gamma_i(\gamma_i-1}}$

SUBSCRIPTS

123	refer to regions in fig.1
T	transmitted shock parameter
bl	boundary layer parameters (see fig.2)

1. Introduction

Simple shock tube theory is well known. In this section an account of a deviation from this simple theory is described.

In fig.1 an idealized wave diagram of simple shock tube flow has been drawn. From this diagram, it is seen that constant conditions will prevail at the end of the tube, subject to the arrival of disturbances arising from; (a) the interaction between the contact surface and reflected shock; (b) arrival of the contact surface, or (c) the arrival of the head, or tail, of the expansion from the high-pressure section. In practice, however, it is found that rapid cooling of the gas at the end plate, behind the reflected shock wave, occurs far sooner than can be accounted for by the arrival of expansion waves from the high-pressure section, or by the arrival of the contact surface. Reflections from the interaction between the contact surface and reflected shock cannot be held responsible for the cooling since it occurs even when these reflected disturbances are compression waves. Clearly we must look for some alternative mechanism.

At present, there are two possible explanations. One of these concerns the instability of the contact surface[2,3] after interaction with the reflected-shock wave, and the other considers the effect of bifurcation[4] of the shock which has passed through the contact surface (i.e. the transmitted shock see fig.1).

The interface instability mechanism is one whereby, after interaction with the reflected shock, the breaking up and spreading of the contact surface into the hot gas results in mixing and cooling. This mechanism has been suggested by Bird et al and is adopted by Lapworth as an explanation of the early cooling of the hot gas observed in experiments designed to investigate the duration of the hot flow, and performed over a range of primary shock Mach numbers with helium as driver gas and nitrogen as driven gas.

In the bifurcation mechanism, the flow of gas through the two oblique shocks which form the foot of the bifurcated shock (see fig.2) emerges with a higher velocity relative to the normal shock than the flow which has passed through the normal shock. In the case of the shock travelling into the expanded driver gas (i.e. the transmitted shock) the flow which has passed through the normal part of the shock moves with contact surface velocity, but the flow which has passed through the bifurcated foot is moving faster and will therefore reach the end wall sooner than the contact surface. Experimental evidence in support of this mechanism is described in reference 4.

Unfortunately, both theoretical models predict that cooling will occur as a result of the particular mechanism in question, for primary shock Mach numbers greater than approx 3.6 when helium is used as driver gas and nitrogen as test gas. Using these gases it is impossible to observe the one mechanism without the influence of the other. It is suggested in reference 4 that if argon is employed as the test gas and either helium or hydrogen is used as driver gas, interface-instability cooling should occur in both cases at significantly lower values of the primary shock Mach number than bifurcation cooling.

With regard to bifurcation cooling, with nitrogen as the test gas, for example it is necessary to take into consideration the fact that the shock which approaches the contact surface is already bifurcated (this will be so for diatomic gases). This suggests that the means for producing a region of faster flow of cold gas to the end plate is already present before the shock meets the contact surface. When argon is employed, however, there is ample evidence[6,7] to show that the shock which approaches the contact surface is not bifurcated for primary shock Mach numbers greater than 2.8; hence bifurcation of the transmitted shock should then be accomplished solely by its interaction with the boundary layer. This is clearly of great significance as no bifurcation effects will be present with argon until the transmitted shock bifurcates, thus allowing the effects of any interface instability which occur to be readily observed.

A series of experiments designed to investigate the bifurcation of the transmitted shock when argon is used as test gas and helium as the driver gas is described below.

2. Theory

A detailed discussion of the theory is to be found in ref.4. A brief description with the relevant equations is given below.

The model is based on the approach used by Hess[5] and Mark[6], in which the shock wave is considered to interact with a boundary layer of unspecified thickness, moving at the wall velocity, and having no thermal or velocity gradients normal to the wall. Shock-fixed coordinates are employed, and the boundary layer is considered to be brought to stagnation conditions under the foot of the shock. If the stagnation pressure of the boundary layer gas is greater than the pressure behind the normal shock, the gas is able to enter the region behind the normal shock and no bifurcation occurs. Alternatively, if the stagnation pressure is less than the pressure behind the normal shock the boundary layer gas is forced to gather under the foot of the shock resulting in a bifurcated shock pattern (see fig.2). It can then be shown[4] that the flow which emerges through the rear limb AB of the bifurcated foot has a greater velocity relative to the normal shock than the flow which has passed through the normal shock. In the transmitted shock case the result is a flow of cold driver gas to the end plate, causing cooling of the hot gas.

As both theory and experiment[6,7] have shown that no bifurcation occurs for the shock which approaches the contact surface for $M_1 > 2.8$ when argon is used as test gas, only the equations relevant to the transmitted shock will be given (see ref.4 for the complete theory).

If $M_{bl} = U_{bl}/a_1$ is the boundary layer Mach number then for $M_{bl} < 1$ the boundary layer stagnation pressure may be obtained using the equation:

$$\frac{p_{st.bl}}{p_3} = \left[1 + \frac{\gamma_1 - 1}{2} M_{bl}^2\right]^{\frac{\gamma_1}{\gamma_1 - 1}}$$

and for $M_{bl} > 1$ using the equation

$$\frac{p_{st.bl}}{p_3} = \frac{\left[\frac{(\gamma_1+1)}{2} M_{bl}^2\right]^{\frac{\gamma_1}{\gamma_1-1}}}{\left[\frac{2\gamma_1}{(\gamma_1+1)} M_{bl}^2 - \left(\frac{\gamma_1-1}{\gamma_1+1}\right)\right]^{\frac{1}{\gamma_1-1}}}$$

where for the under-tailored case,

$$M_{bl} = A_{31}\left[\frac{P_{73}+\alpha_3}{\delta_3\gamma_3(\alpha_3 P_{73}+1)^{\frac{1}{2}}} + \frac{2A_{53}}{(\gamma_1-1)}\left[1-(P_{65})^{\beta_1}\right]\right]$$

and for the over-tailored case,

$$M_{bl} = A_{31}\left[\frac{P_{73}+\alpha_3}{\delta_3\gamma_3(\alpha_3 P_{73}+1)^{\frac{1}{2}}} - \frac{A_{53}\delta_1(P_{65}-1)}{(\alpha_1 P_{65}+1)^{\frac{1}{2}}}\right]$$

Values of a_5, A_{13}, P_{21}, P_{52}, T_{21}, T_{51}, U_{21}, M_{bl}, u_3/a_3 versus M_1 given in fig.3 a-i. In fig.4 values of $p_{st.bl}/p_3$ and P_{73} versus M_1 are presented. Bifurcation of the transmitted shock may be expected for $\frac{p_{st.bl}}{p_7} < 0.8$, which is seen to occur for $M_1 > 4.3$ in the present case where helium is used as the driver gas and argon as the test gas.

The experiments described below were designed to ascertain whether or not bifurcation of the transmitted shock occurs when argon is the test gas.

3. Experimental Apparatus

A detailed account of the NPL 6 × 3½ inch shock tube has been given by Holder, Stuart and North[8].

4. Experimental Results

In fig.5 Schlieren photographs of the reflected shock in argon for a variety of primary shock Mach numbers are shown. As has been previously observed[6,7] the shock remains plane with no bifurcation.

Using the equation

$$x = \frac{L}{2}\left\{\frac{1-U_{21}}{M_1}\right\}\left\{\frac{1-U_{21}}{M_3} A_{12}\right\}$$

where x is the distance of the reflected shock and contact surface interaction from the end plate, it is found that the interaction will only appear within the window area for $M_1 \geqslant 6$

(a value of x equal to half the ideal shock tube theory value was taken in this calculation). Hence the photograph reproduced in fig.6 is that of a transmitted shock for $M_1 = 6$. Note that a large degree of bifurcation occurs. Only one side can be seen as a certain amount of fogging of the plate has hidden the bifurcation on the other side.

In fig.7 a series of photographs taken at $M_1 = 6$ shows that initially after passing through the contact surface the shock moves very slowly (in fact it appears to move towards the end wall initially but this is probably due to a variation from run to run). This event was predicted in reference 4. The equation for transmitted shock velocity is (in the over-tailored case)

$$U_T = a_3 \left[\frac{(P_{73}+\alpha_3)}{\delta_3\gamma_3(\alpha_3 P_{73}+1)^{\frac{1}{2}}} - \frac{A_{53}\delta_1(P_{65}-{}_1)}{(\alpha_1 P_{65}+1)} \right]$$

Clearly $U_T = 0$ when

$$\frac{P_{73}+\alpha_3}{\delta_3\gamma_3(\alpha_3 P_{73}+1)^{\frac{1}{2}}} = \frac{A_{53}\delta_1(P_{65}-1)}{(\alpha_1 P_{65}+1)}$$

On performing the computation it is found that the required primary shock Mach number for this to occur is $M_1 = 6$ when helium is the driver gas and argon the driven gas. This is in agreement with experiment, and provides a useful confirmation of the value of the rather crude flow used in the theory. Owing to experimental difficulties no tests were carried out for $M_s > 6.08$.

5. Discussion

From the experiments described above it is found that bifurcation of the transmitted shock does occur in the higher Mach number cases where helium is the driver gas and argon is the driven gas.

Further confirmation of the usefulness of the undeniably crude theoretical model was obtained when it was observed that the transmitted shock remains more-or-less stationary initially after reflected-shock and contact surface interaction, as predicted at $M_1 = 6$ by this model.

Finally the present results suggested that argon should be used as test gas with either helium or hydrogen as driver gas in an investigation of the gas temperature close to the end wall of a shock tube. Under these conditions it is possible that the effects of interface instability on hot flow duration at the end plate may be observed without the influence of bifurcation effects. For helium as driver gas and argon as driven gas, instability cooling effects should appear (ideally) for $M_1 > 3.8$ whereas bifurcation cooling effects should occur for $M_1 > 4.3$. Since the interaction between the reflected shock and the contact surface appears within the window section only for the $M_s = 6$ case no photographs of transmitted shocks below this Mach number are at present available. Hence the lowest primary shock Mach number for the appearance of transmitted shock bifurcation has not been experimentally determined.

Acknowledgement

The computations were performed by Miss B. Redston.

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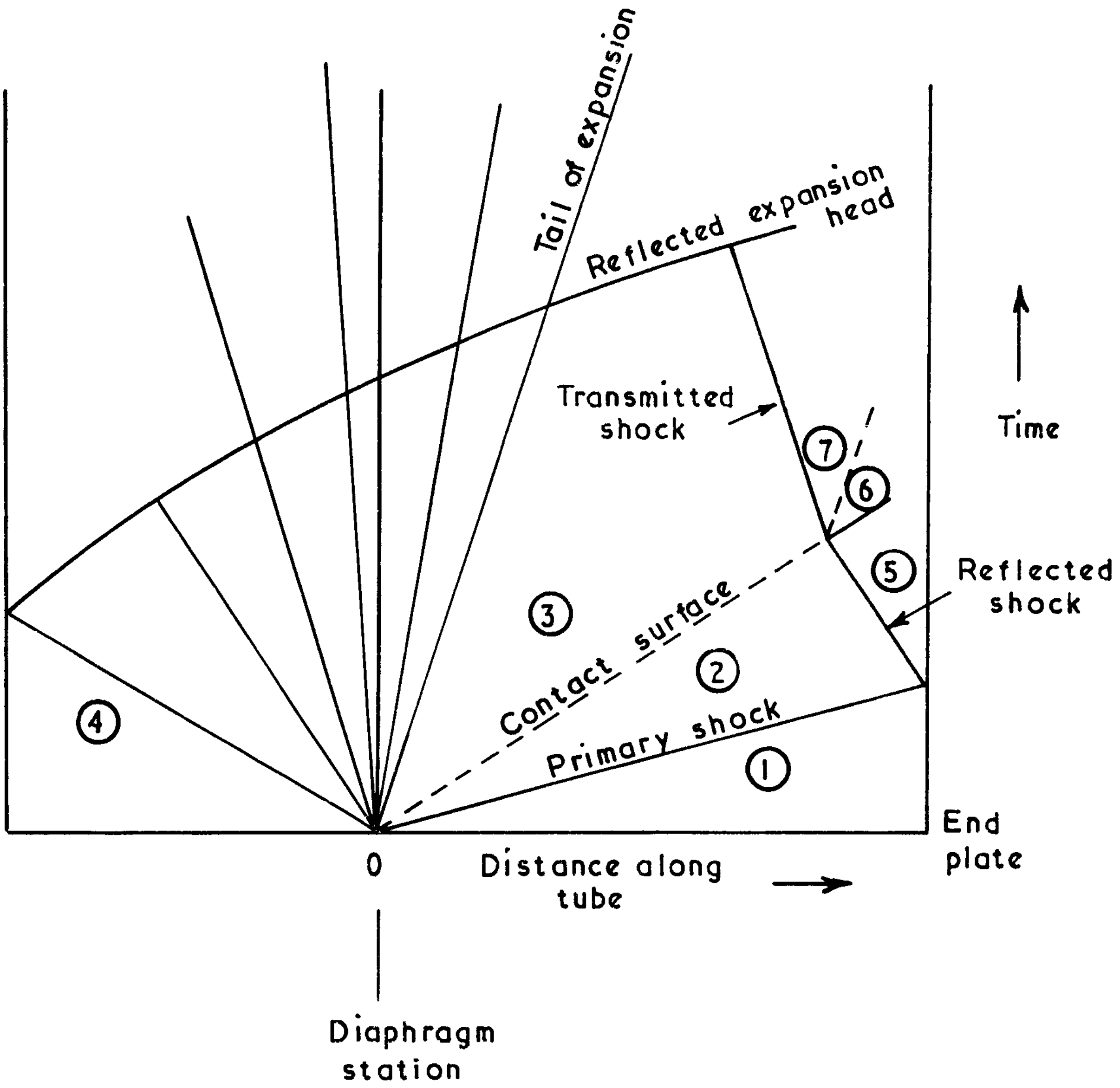
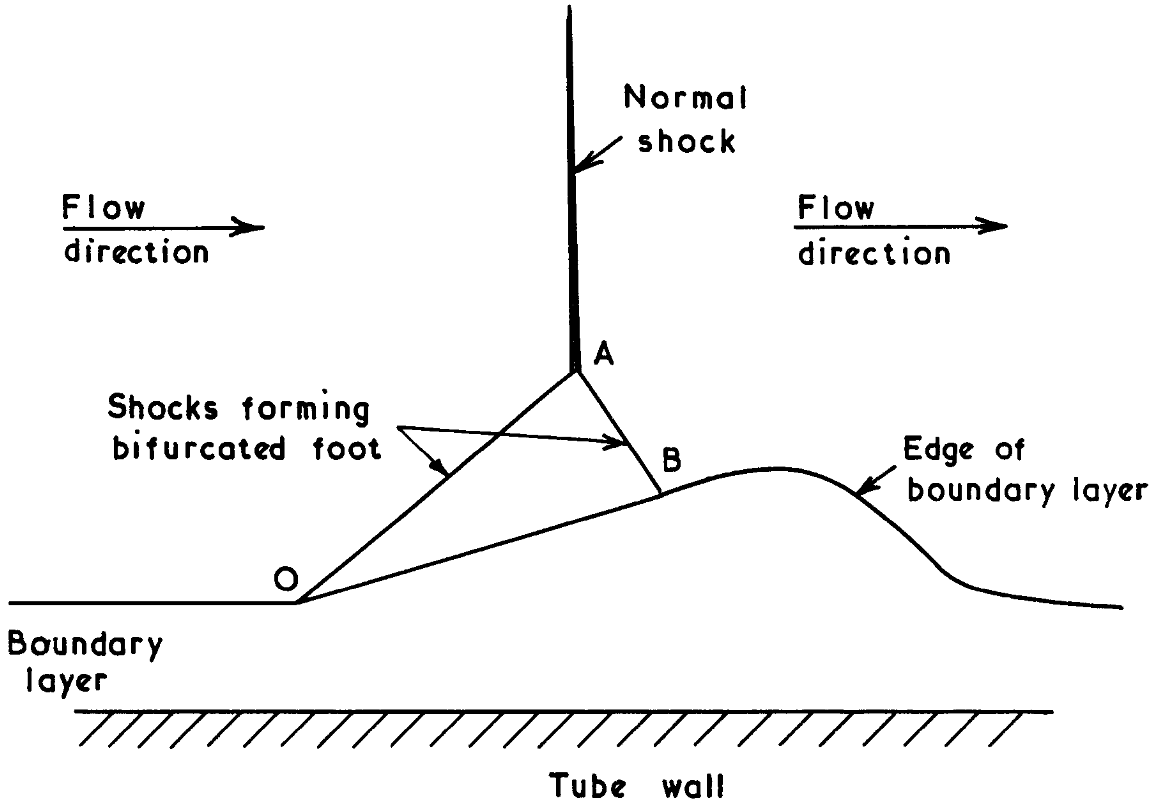
FIG. 1



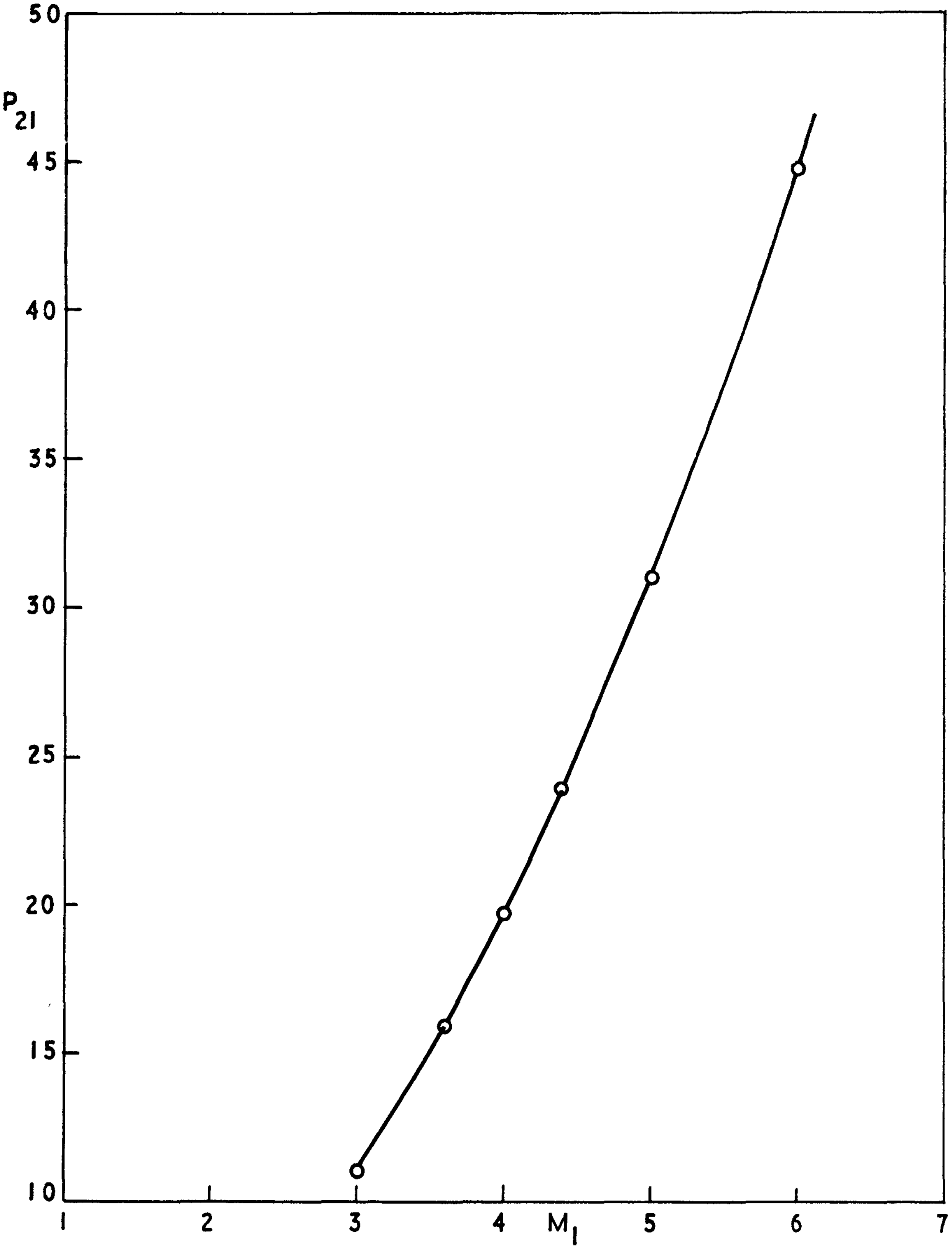
Wave diagram —— simple shock tube flow

FIG. 2



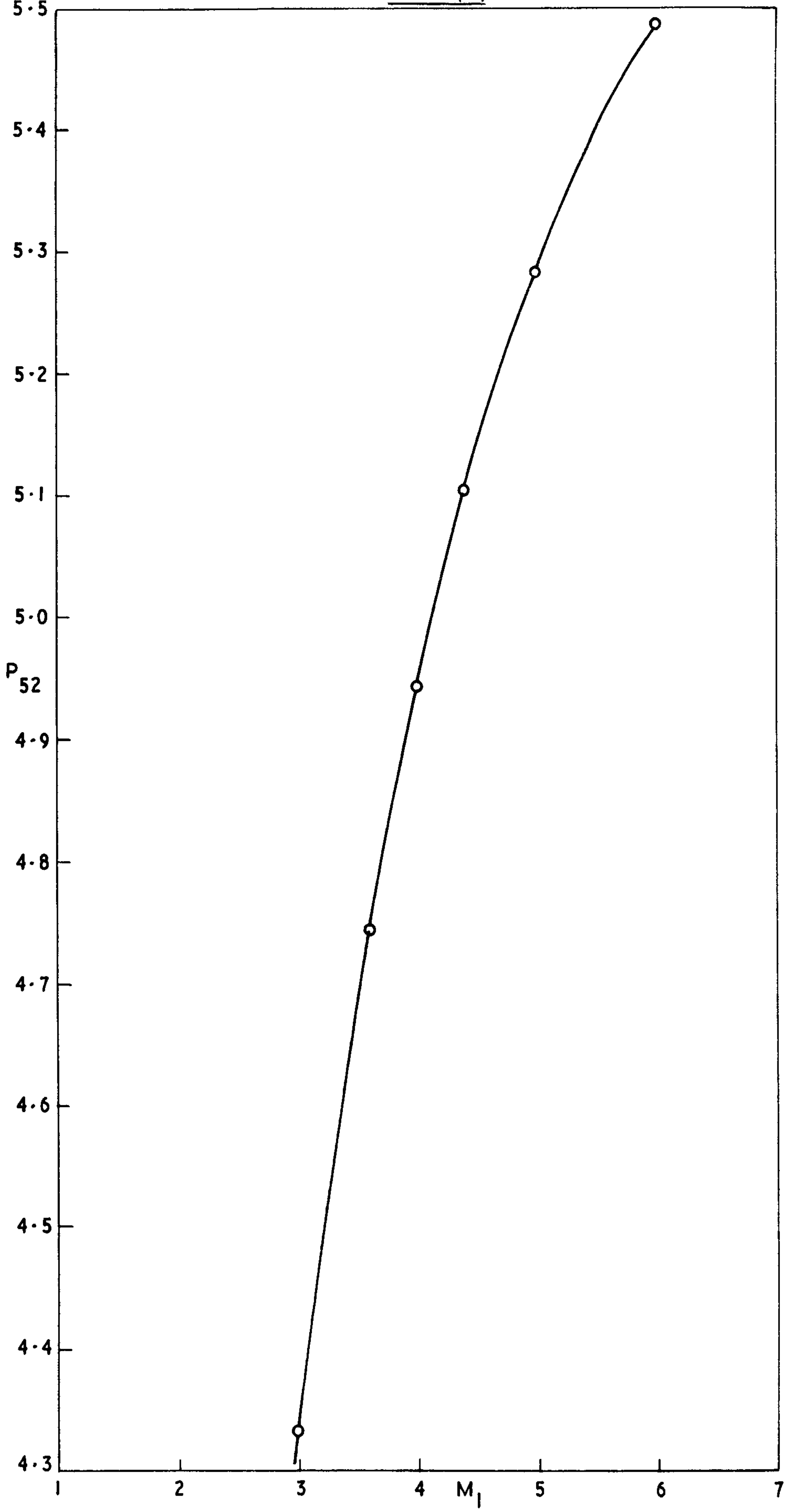
Bifurcated shock

FIG. 3(a)



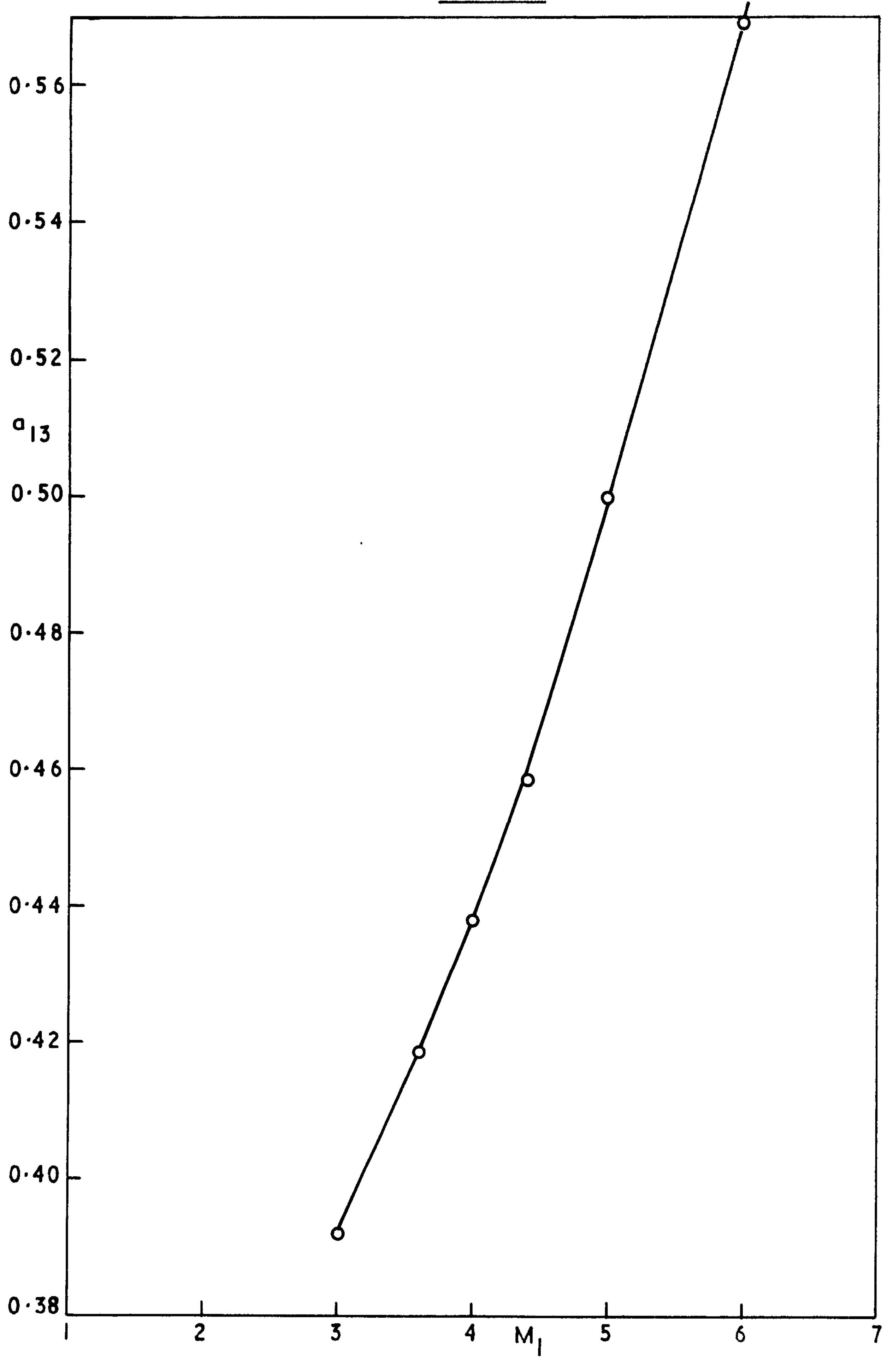
P_{21} vs M_1 for Helium as driver gas and Argon as driven gas

FIG 3.(b)



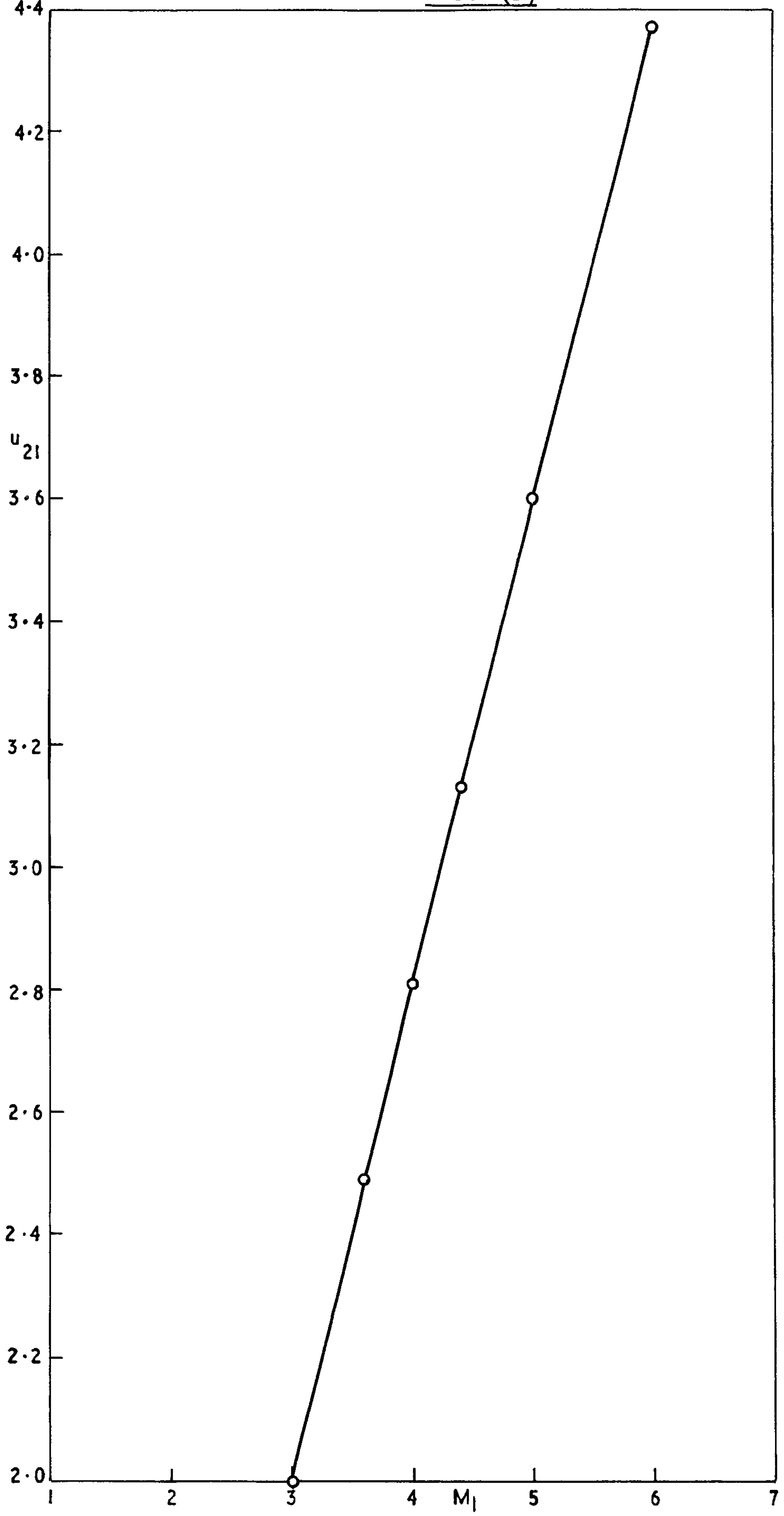
P_{52} vs M_1 for Helium as driver gas and Argon as driven gas

FIG. 3(c)



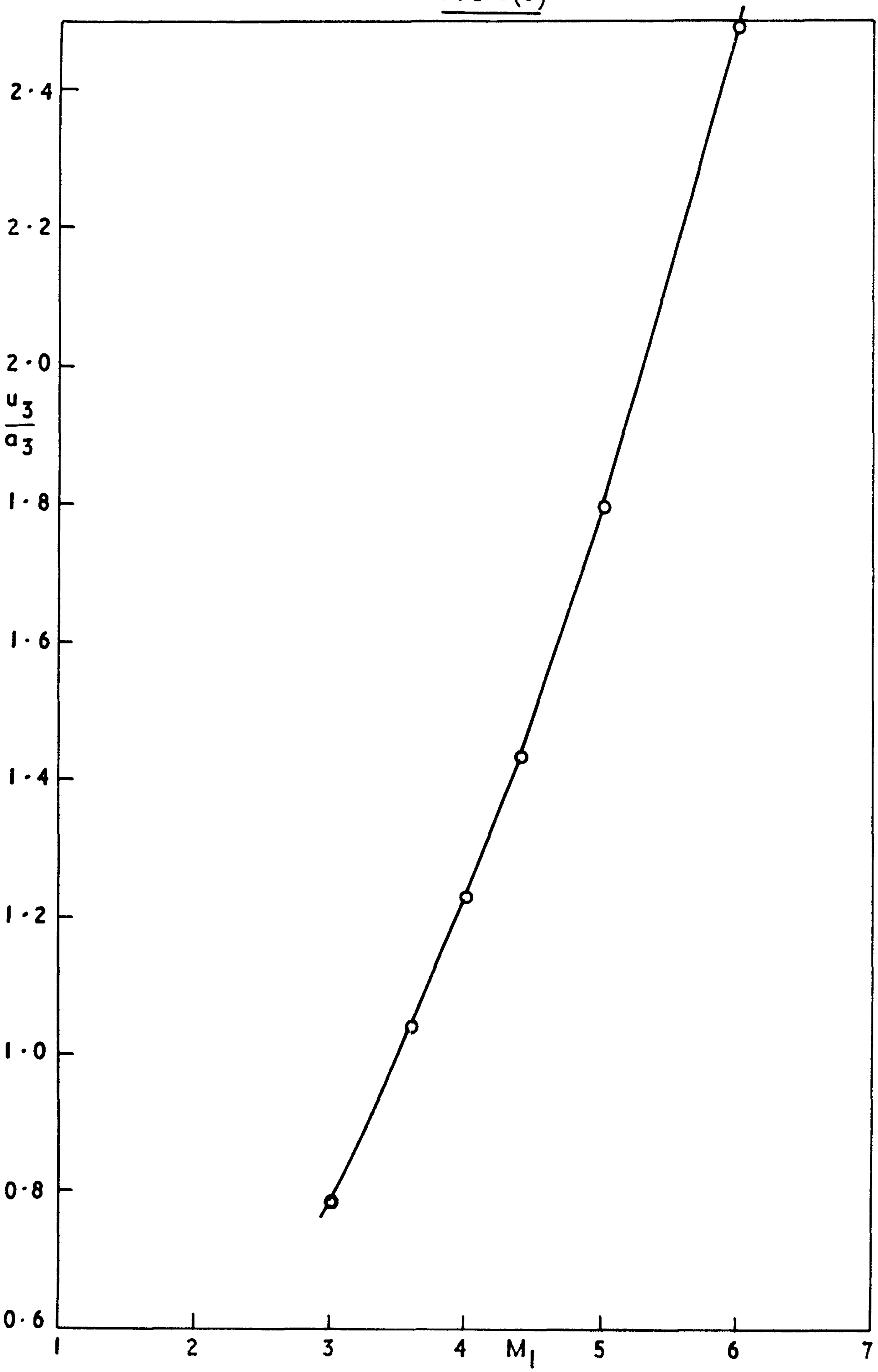
a_{13} vs M_1 for Helium as driver gas and Argon as driven gas

FIG. 3(d)



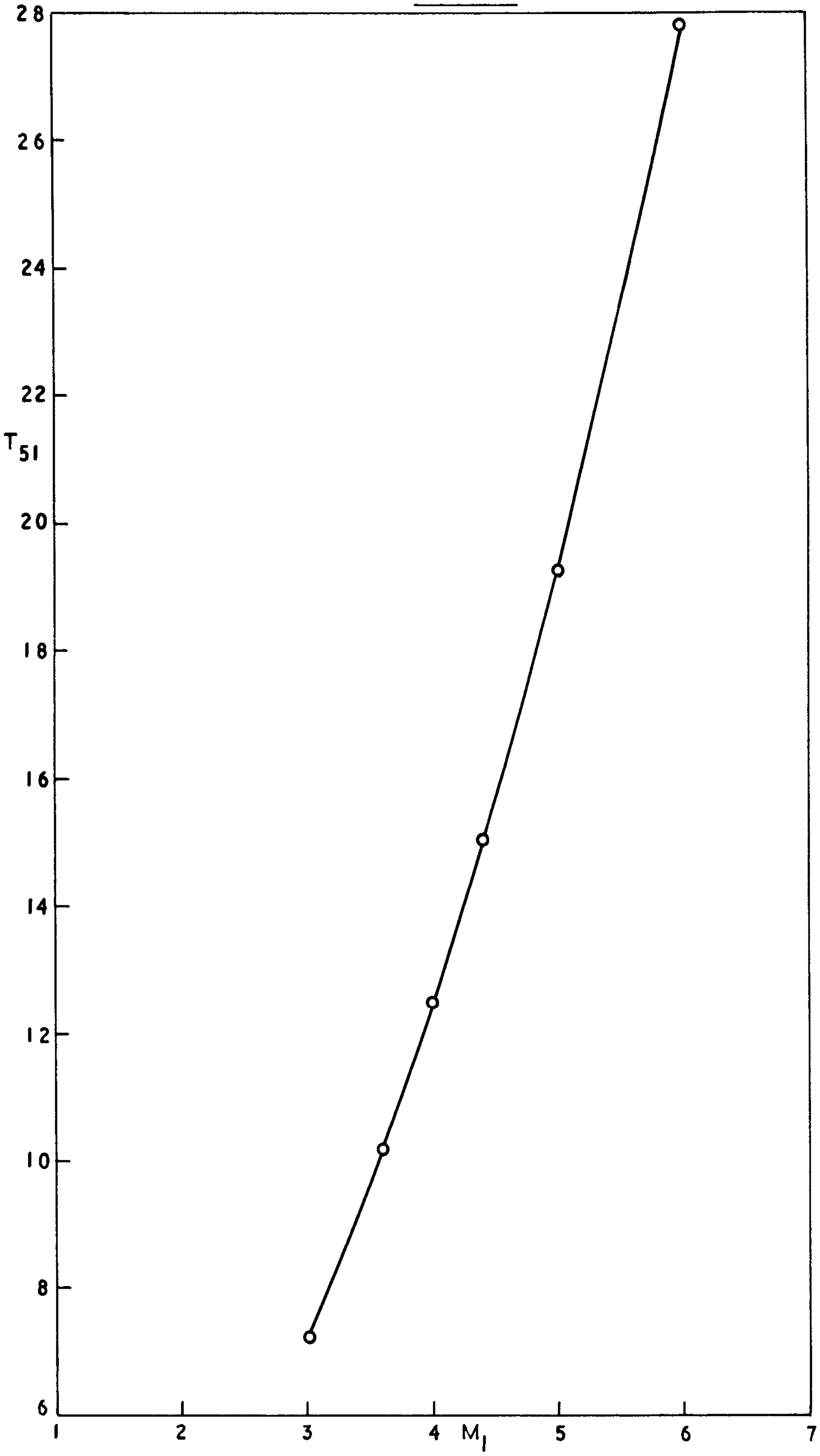
u_{21} vs M_1 for Helium as driver gas and Argon as driven gas

FIG. 3(e)



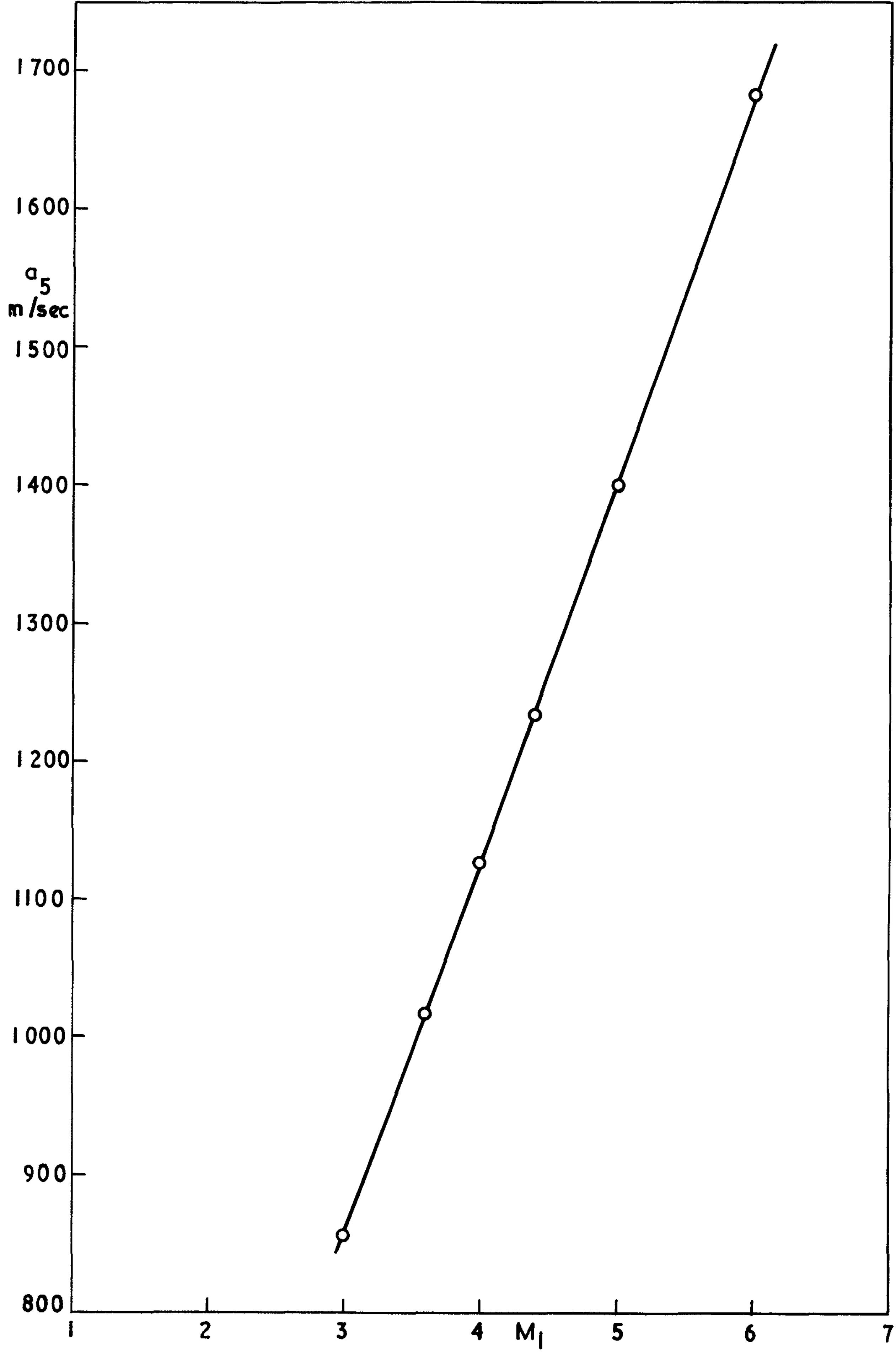
$\frac{u_3}{a_3}$ vs M_1 for Helium as driver gas and Argon as driven gas

FIG. 3(f)



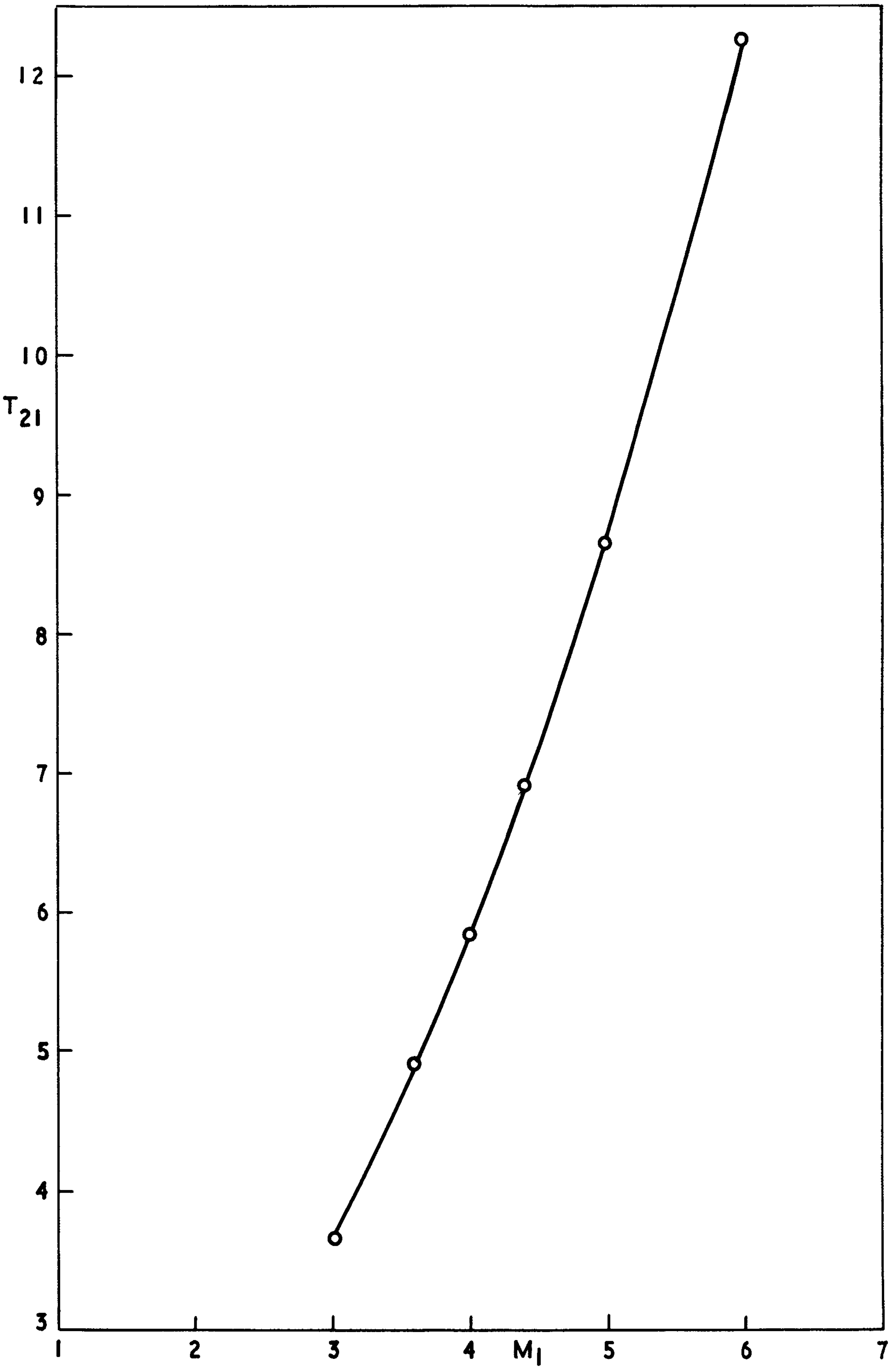
T_{51} vs M_1 for Helium as driver gas and Argon as driven gas

FIG 3.(g)



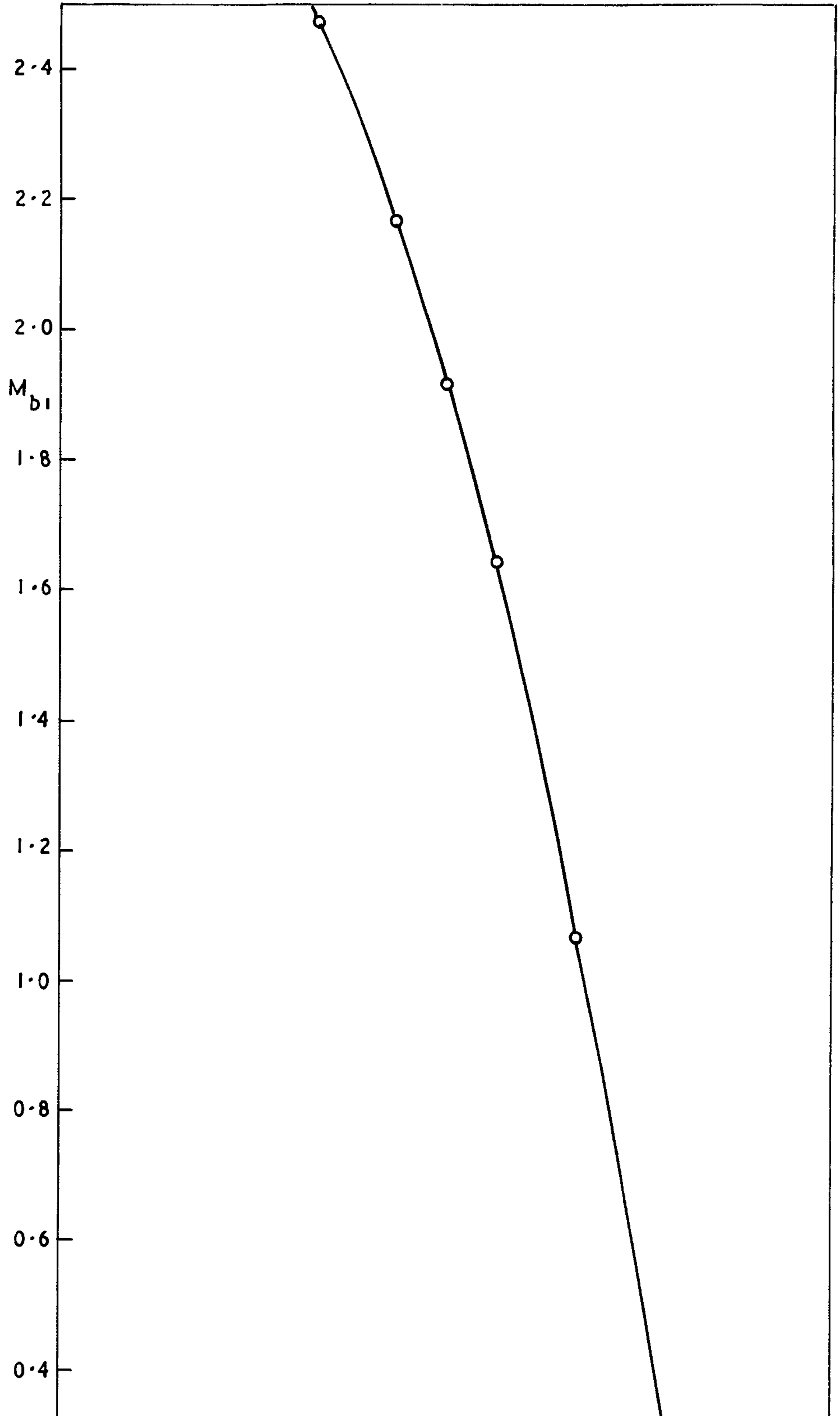
a_5 vs M_1 for Helium as driver gas and Argon as driven gas

FIG. 3(h)



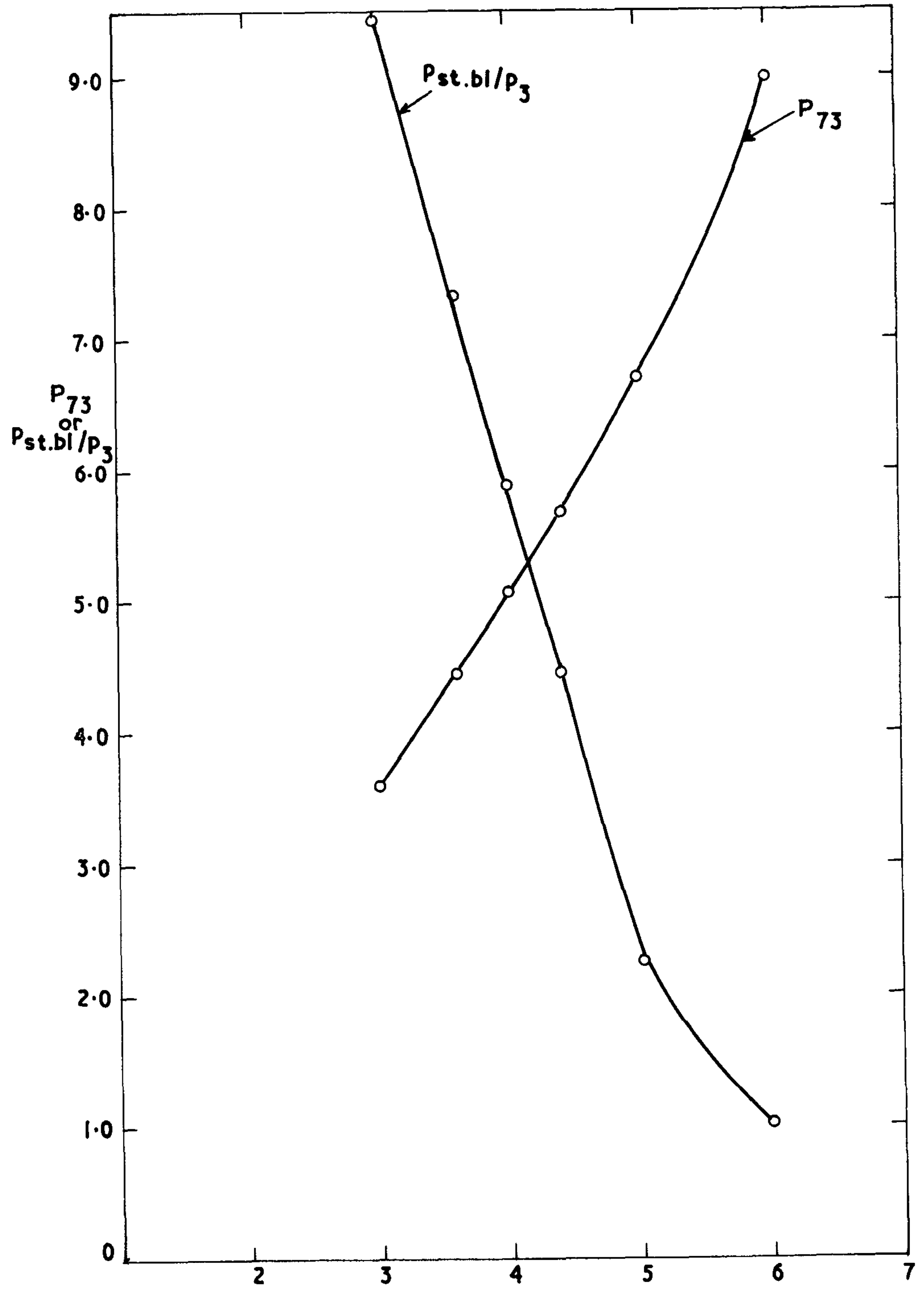
T_{21} vs M_1 for Helium as driver gas and Argon as driven gas

FIG 3(i)



M_{b1} vs M_1 for Helium as driver gas and Argon as driven gas

FIG. 4.

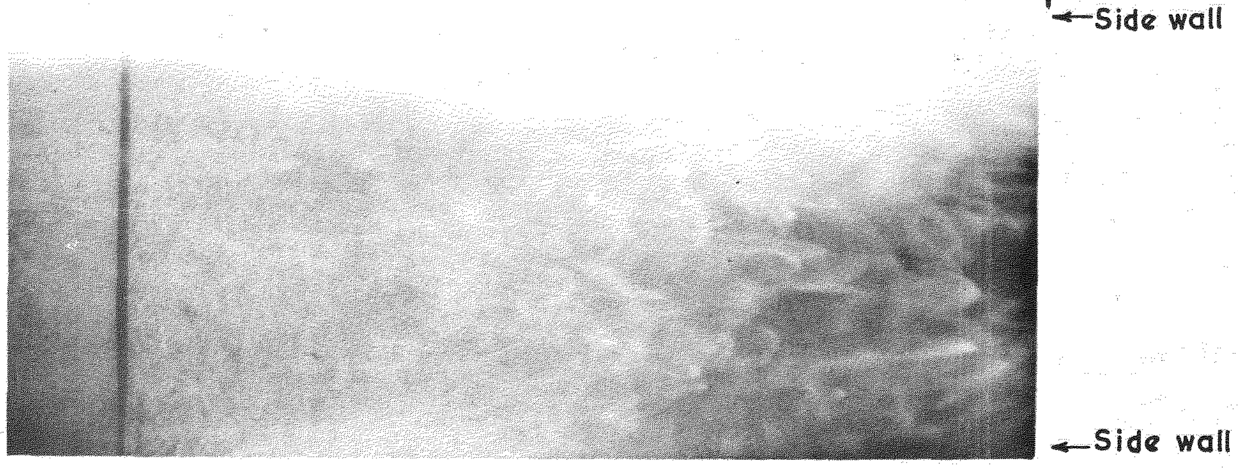


P_{73} and $p_{st.bl}/p_3$ vs M_1 for helium as driver gas and argon as driven gas

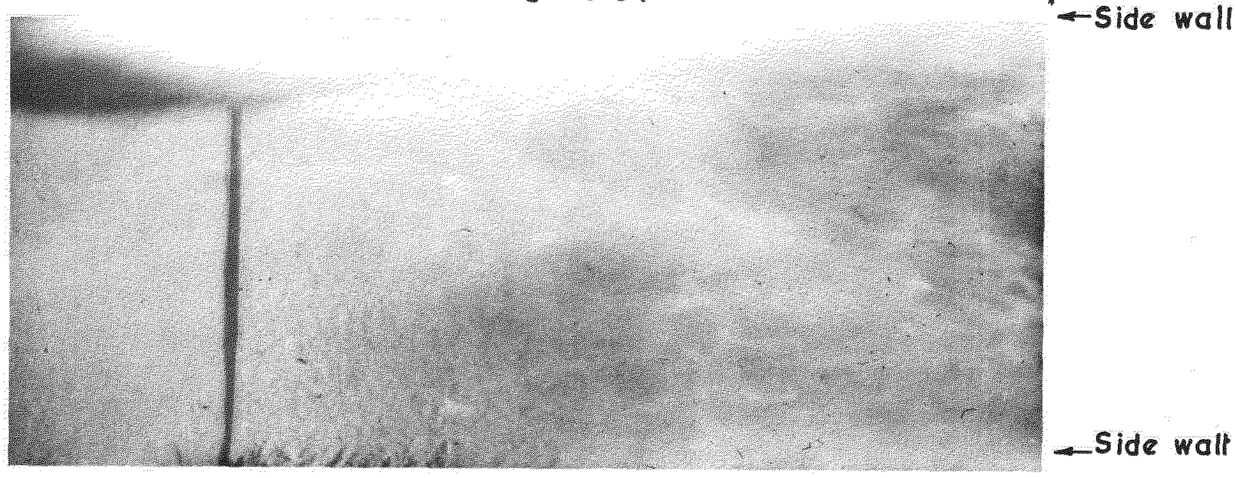
FIG. 5

(a) $p_1 = 26{\cdot}4$ mm/Hg
$M_s = 3{\cdot}91$

(b) $p_1 = 9$ mm/Hg
$M_s = 4{\cdot}97$

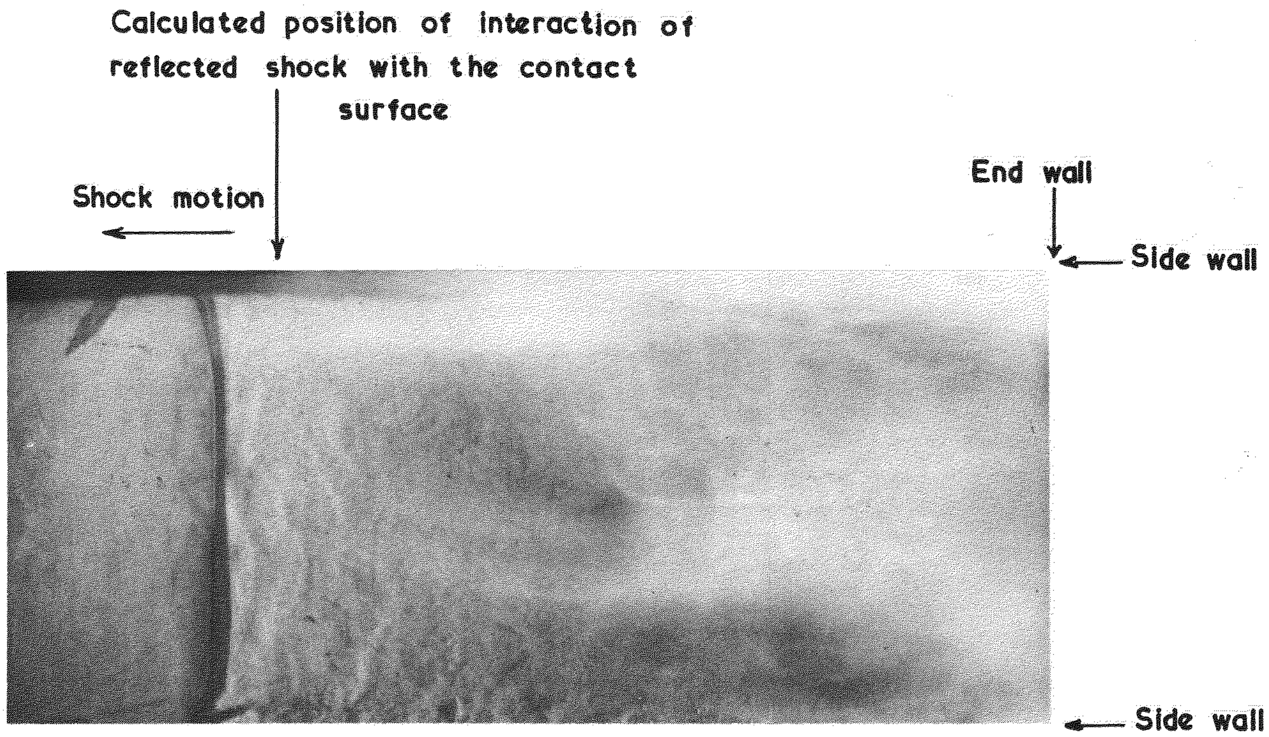


(c) $p_1 = 5$ mm/Hg
$M_s = 5{\cdot}54$



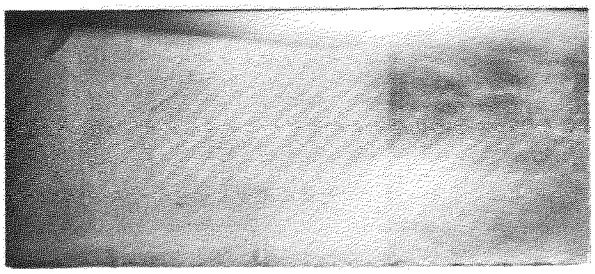
Reflected shock pictures using helium as driver gas and argon as driven gas

FIG. 6



Schlieren photograph showing that the shock transmitted through the contact surface is bifurcated; helium is the driver gas and argon the driven gas, and $M_S = 6{\cdot}00$, $p_1 = 2$ mm/Hg.
The upper end of the shock is hidden in this photograph.

FIG. 7

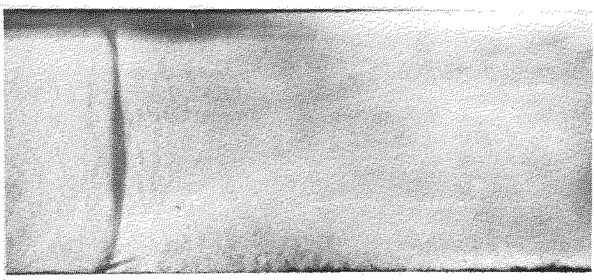


1

Delay 200 μ sec

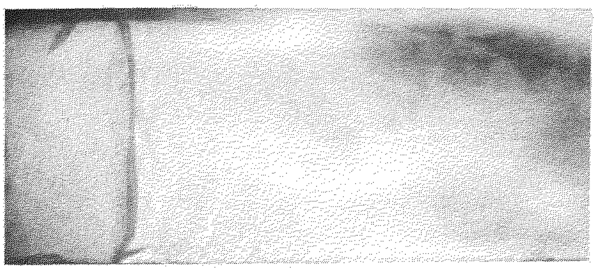
$p_1 = 2\,mm/Hg$

$M_s = 6{\cdot}08$



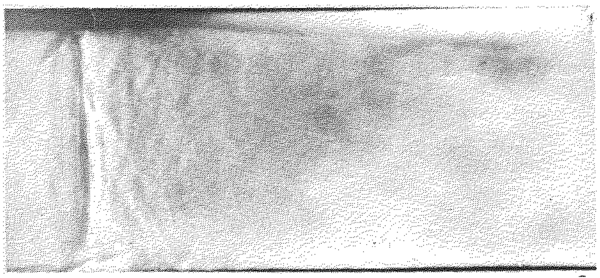
2

Delay 300 μ sec



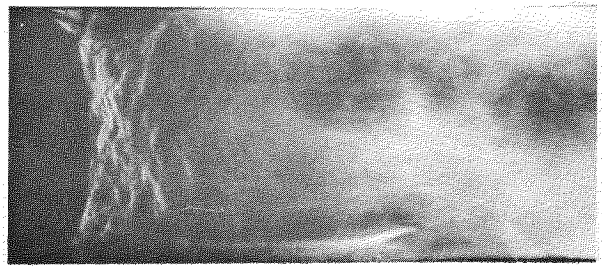
3

Delay 330 μ sec



4

Delay 345 μ sec



5

Delay 360 μ sec

Schlieren photographs showing the reflected shock (1) and the transmitted shock (2) to (5). Note that from (2) to (3) there is almost no velocity of the transmitted shock relative to the tube. (Helium driver, argon driven)

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