MICROWAVE MEASUREMENTS ON SHOCK WAVES IN AIR *

by

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The microwave attenuation by shock waves in air was investigated in the Mach No. range of 8 - 12 and at pressures 1-5 mm Hg. It is shown that an analysis of the time dependence of the attenuation yields important information regarding (a) the maximum electron-density (b) the build-up of the electron density and the beginning of the shock, (c) the electron density near the contact surface, and (d) the length of the heated slug section.

We have investigated also the effect of transitions from a larger diameter shock tube to a smaller tube on the maximum microwave attention, on its time dependence, and on the Mach No. In particular, we have studied the effect of shorter and larger taper sections as well as abrupt transitions for various Mach Numbers and initial pressures.

Introduction

Microwave attenuation by ionised gases is one of the methods that can be used in the investigation of the properties of shock waves. Most of these investigations in the past have been concerned with the peak attenuation of the microwaves[1,2,3]. Little attention has been paid to the time dependence of the attenuation as the shock passes the point of observation. We report briefly in Section I the results of extensive investigations on the shape of the microwave attenuation curve and to what extent it throws light on the physical processes between the shock front and the contact surface[4]. In the second section we give results on the change in the Mach No., changes in the peak maximum attenuation and shape of the attenuation for different shock tube transitions. It is shown that the techniques of microwave diagnostics are valuable tools in the investigation of hydrodynamic phenomena behind the shock tube transitions.

Experimental Techniques

The experimental arrangement is shown in Fig. 1. The high pressure chamber of 1" filled with hydrogen gas was connected by 60 cm long conical taper to the ½" shock tube. The shocked gas was air at pressures from 1 - 5 mm Hg. The shock tube consisted of sections "a" of variable length before the point of observation which was a short teflon section followed again by a regular metal tube and dump tank. The microwave system shown was essentially a transmission system, although (not shown in the Fig.) it permitted the measurement of the reflected power. The klystron was followed by an isolator, attenuation SWR meter, tuner, and a waveguide section with a central hole through which the teflon shock tube passed and terminated in a crystal detector.

The resolving distance, defined as the distance which the microwave system registers an electrical disturbance was about 13 mm or about the width of the waveguide. This corresponds to about 2.5 μs at a shock speed of 4900 m/sec.

The Mach No. was measured by sets of miniature spark plugs placed symmetrically about the measuring waveguide section. Experiments described in Section II used a number of such sets of spark plugs.

The details of the systems, the calibration procedure, and resolving power are described elsewhere[4].

I. MICROWAVE ATTENUATION OF SHOCKED AIR

The microwave attenuation is related to the ratio of the voltage level at the detector by the equation:

$$\alpha\,(db/cm) = \frac{8.4}{2\,l_{eff}} \ln V_0/V_1 \qquad (1)$$

where l_{eff} is the effective microwave length about 0.73 times the dimension of the waveguide, V_0 and V_1 the undisturbed and disturbed voltage level. The attenuation is related to the electron density by

$$\alpha^2 = \frac{\omega^2 \varepsilon}{2c^2}\left\{-1 \pm \left[1 + \left(\frac{4\pi\sigma}{\varepsilon\omega}\right)^2\right]^{1/2}\right\} \qquad (2)$$

for low conductivities this formula can be approximated by

$$\alpha \simeq \frac{16\sqrt{\pi}}{3}\,\frac{e^2 N_e \gamma}{m\,\omega^2} \qquad (3)$$

where ω is the microwave frequencies

N the electron density

e and m the charge and mass of the electron

γ the mean collision frequencies in the ionized gas

In order to correlate this with theory one has to know all the possible reactions of air and their rate contents. Some of these are still in doubt. We used the cross-sections given by Lamb and Lin[5] and also the corrections suggested by Huxley[6].

The results shown here are those of $p_1 = 5$ mm Hg. The testing time available was sufficiently long to enable significant interpretation.

In Fig. 2, the experimental data and calculated attenuations are shown. Fig. 3 shows the effect on the peak attenuation as a function of the Mach No., keeping p_4/p_1 constant but using different length of shock tube "a". The change in the Mach No. is caused by the (linear) dependence of the deceleration of the shock on this distance. After a minimum length "a" the microwave attenuation for a given Mach No. is constant and is not a function of "a".

Important information can be obtained from the shape of the voltage-time curve. Typical photographs shown in Fig. 4(a-c). Such photographs are analysed in terms of the attenuation as a function of time. Fig. 5 gives such an analysis for the conditions shown in Fig. 4a as well as for other Mach Numbers. For electron densities larger than about 10^9 electrons /cm^3, the rise of the attenuation (and also the electron density) is nearly linear with time. This is followed by a sudden decrease from the peak of the electron density and a long tail extending into the section of the colder driver gas.

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The following conclusions can be summarised briefly:

1. The peak attenuation is larger by about a fraction of 5 then that predicted by theory.

2. The peak electron density for a given Mach No. is independent of the history of the shock provided the shock has traversed a minimum distance "s".

3. The shape of the electron density - time curve gives information regarding the onset of the ionisation, its rate, and the arrival of the cold driver gas. The sudden discontinuity, identified as the contact surface is followed by a long tail of relatively low electron density, the origin of which is not fully understood. Usual shock tube theories do not predict such an effect. Possibly interface mixing, extending over a large region, may be a contributing factor.

II. EFFECT OF CHANGES IN CROSS-SECTIONAL AREA ON THE MACH NO. AND ON THE ELECTRON DENSITY

Introduction

The problem of the motion of a shock wave passing through a sudden or gradual contraction of the cross-sectional area has been treated by a number of authors[7,8,9,10,11]. A recent review by Chester[12] analyses the various approaches. The steady state theory describes the conditions of the shock sufficiently far downstream where the significant shock parameters are independent of time. The linearised theories in one form or another predict a Mach speed which is higher than that obtained from the steady state theory. The experimental results which are very sparse seem to fall between those two extremes[13,14]. In all these theories the re-reflected wave, which may occur either at the shock tube transition or at the contact surface, is not taken into account. As suggested by Whitham[9] this secondary shock may change the nature of the primary shock and in some cases overtake it. We report here briefly on measurements of the microwave attenuation by the ionised gases behind such transitions which throw light on some of these phenomena.

Experimental results of shock speed measurements

The results refer to two extreme transitions; an abrupt passage from a 1" to ½" tube and a gradual taper of 0.56° inclination. In both cases the shock had passed a distance of 200 cm from the high pressure chamber before the transition. One would expect in our experimental arrangement that the abrupt passage would approximate the steady state theory prediction and the gradual taper, the linear theory.

The shock speed was measured by spark plugs placed 10 cm apart. The speed was measured with sets of these placed upstream and downstream of the transition. This gives the average speed between these two points. The average Mach No. as a function of the distance "s" from the abrupt or conical transition at pressures of 5 and 1 Hg is shown in Fig. 6. and 7. The shock speed increased after the transition, reaches a maximum, decreases and settles down to a steady deceleration. The position of the maximum and the sharpness of the maximum are a function of the initial pressure, tending to flatten out as the pressure is higher*. Since most measurements reported in the literature were made at higher pressures and low Mach numbers, this peak seems to have gone unnoticed. Neither of the two theories predict this phenomenon. We suggest that the re-reflected wave effects the shock speed in particularly the region from 0 - 70 cm after this transition. The rate of shock speed attenuation is greater than measured in the conventional shock tube arrangement as in Section I. This is not surprising since the boundary layer effects after a cross-sectional change are expected to be more complicated.

Measurements of Microwave Attenuation

Microwave attenuation photographs are shown in Figs. 8(a-d) and Fig. 9 (a-c). These should be compared with those shown in Fig. 4(a-c). In fig. 8(a-d) the case of the abrupt transition, the following features should be noticed.

1. There is a time evolution of the attenuation profile. In Fig. 8a there is a large attenuation peak. At a distance of 17 cm Fig. 8(b) there are two strong peaks. At still larger distances (Fig. 8c and 8d) there is only one remaining peak (called peak 2) which decreases in intensity as the shock front moves downstream.

2. A small attenuation peak (called peak 1) ahead of the stronger peak (2) grows in intensity as the shock moves downstream. It reaches a nearly constant value for distances larger than 87 cm after the transition.

3. The tail of the decay curve of the intense peak 2 gets longer as the shock moves downstream, and the total time the attenuation is observed increases.

The results of conical transitions and those of abrupt transition are qualitatively similar at distances larger than 50 cm. In all these cases we observe the sharp attenuation peak 1 and a broader attenuation peak 2. Results for different initial pressures and for conical transitions will be presented elsewhere.

Peak (1), the downstream peak, grows primarily as the shock moves in the narrow shock tube. We assume that the electron density arises in the main from the ionisation of hot gases accumulated after passing through the transition. The peak attenuation against Mach No. is shown in Fig. 10 for the abrupt constriction and Fig. 11 for the conical constriction. The attenuation increases with the distance "s" until it reaches a constant value and then behaves similar to that shown in Fig. 2 and 3.

The profile of the microwave attenuation of peak 2 is not understood. In the regions where the shock accelerates i.e. in the region of 0 - 70 cm there seems to be unstable regions of high electron densities which either disappear or alternate rapidly as the shock moves downstream and settles to a steady deceleration. We are tempted to connect this region with the shock-shock phenomena predicted by Whitham[15].

From inspection of Figs. 8 and 9 it is found that there are several mechanisms operative in cooling down the hot region of peak 2. In particular we should like to point out that the decay tail lengthens, very similar to the phenomena found in Section I.

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* In the case of a conical transition, one observes a smaller maximum after one deducts the contribution of the deceleration along the tube.

III. CONCLUSION

The results presented here show that a detailed analysis of the microwave attenuation against time curve yields important information regarding the region between the shock front and the contact surface. It can be used as a tool in the investigations of the hydrodynamic properties of the shock wave behind cross-sectional a.ea changes.

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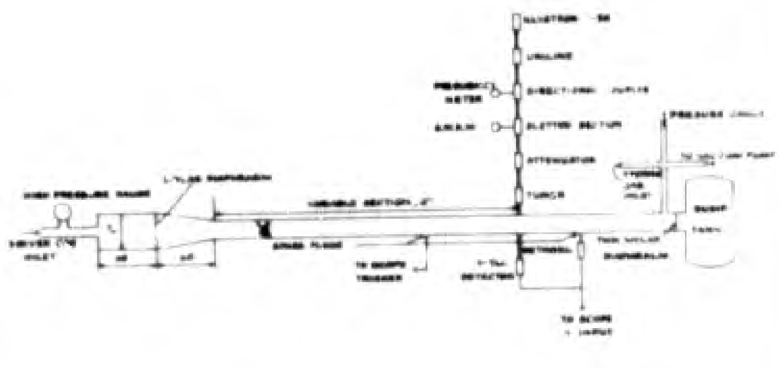

Fig. 1. Experimental arrangement of the microwave system and the shock tube.

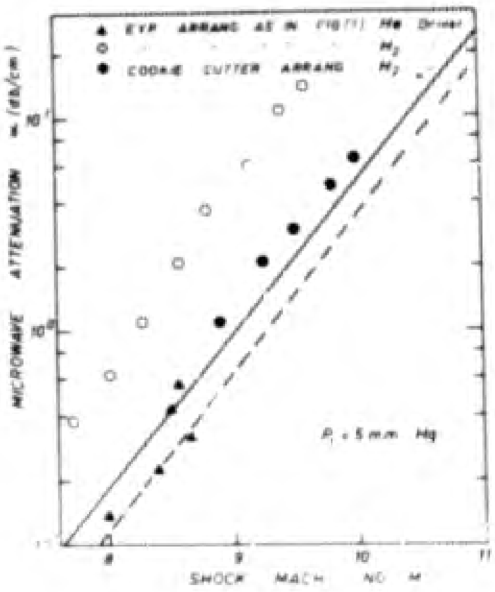

Fig. 2. Peak microwave attenuation as a function of Mach No. p_1 = 5 mm Hg, s = 161 cm. The points O and △ are measured using H_2 and He as driver gas respectively. The solid curve is the calculated attenuation using the cross-section of Huxley[6] and the dotted curve uses the data of Lamb and Lin[5]. The solid circles are data using a "cookie-cutter" method similar to that used in reference 2.

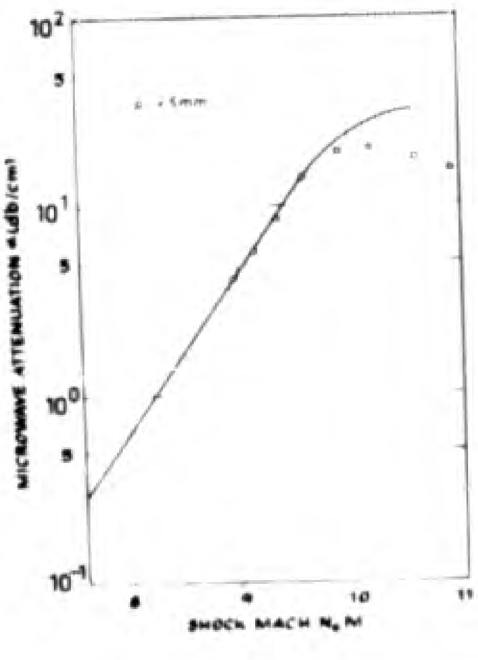

Fig. 3. Peak microwave attenuation as a function of Mach No. The Mach No. is changed using different lengths of shock tubing (the length "s" is changed from 36 to 225 cm). The pressure ratios p_4/p_1 is kept constant. The solid curve is that taken from the experimental values in Fig. 2.

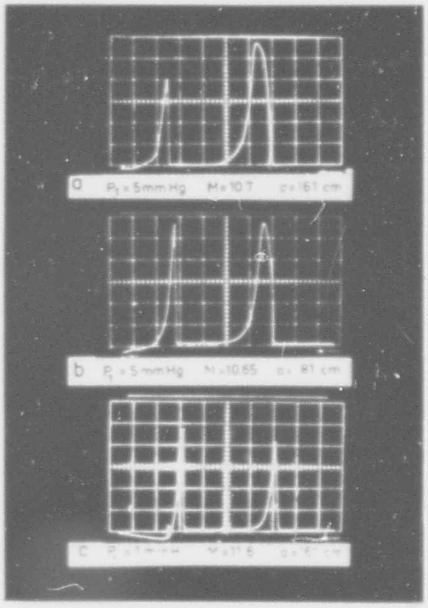

Fig. 4. Photographs of microwave attenuation. Zero microwave level is given by the horizontal line. The first signal is the microwave attenuation. The second sharper signal is a timing pulse from the spark plug. Time scale 20 s/cm.

The conditions of the experiments:

(a) p_1 = 5 mm Hg, M = 10.7; a = 161 cm

(b) p_1 = 5 mm Hg, M = 10.65; a = 81 cm

(c) p_1 = 1 mm Hg, M = 11.6; a = 161 cm

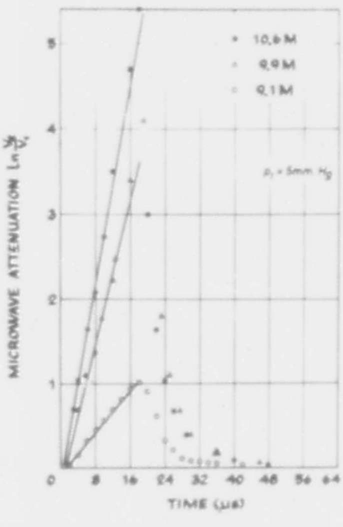

Fig. 5. Rise and decay of the microwave attenuation.

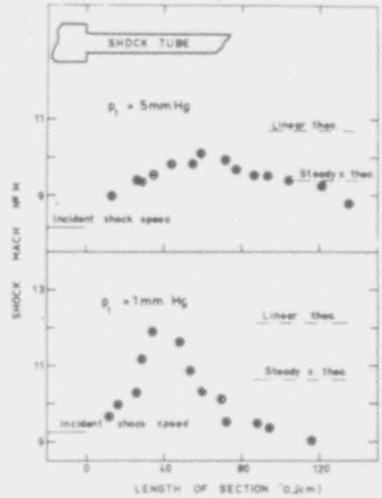

Fig. 6. Shock Mach No. as a function of distance "a" from the abrupt constriction.

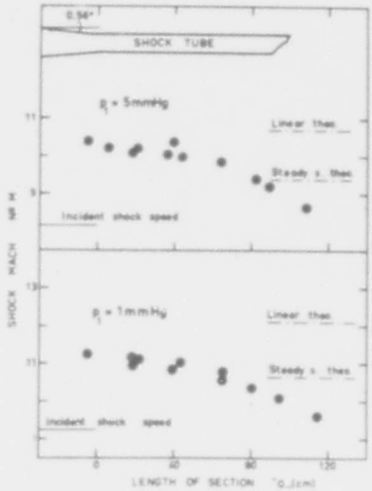

Fig. 7. Shock Mach No. as a function of distance "a" from the end of the conical constriction.

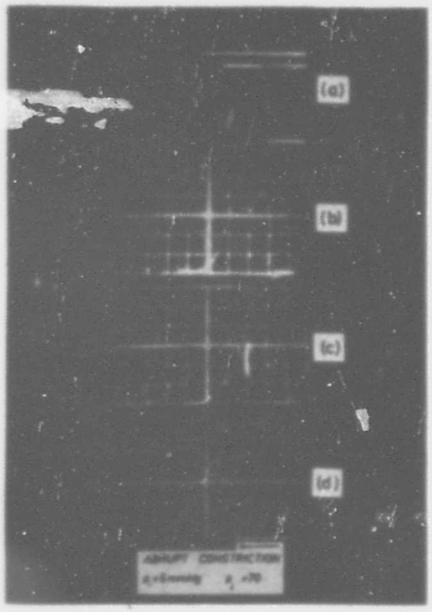

Fig. 8. Photographs of microwave attenuation. In (a) upper trace: spark plugs signal; lower trace: microwave signal. In (b-d) the last sharp peak is a timing pulse from the spark plug. The four photographs are taken at distances 2, 17, 42, and 87 cm from the abrupt passage. Time scale 20 s/cm p_1 = 5 mm Hg, p_4 = 70 at m.

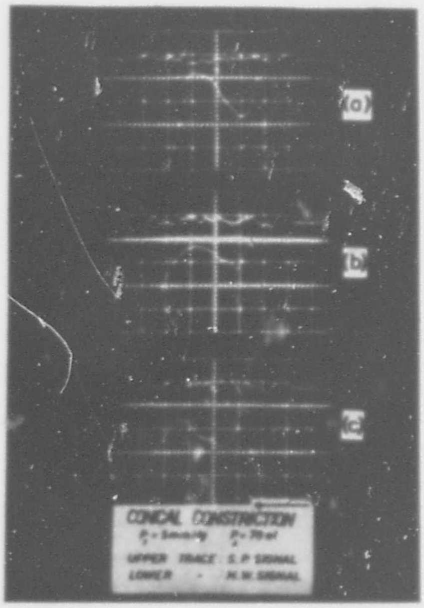

Fig. 9. Photograph of microwave attenuation after a conical transition of 0.56° inclination. The photographs are taken at distances 11, 36, 8/cm from the downstreams end of the conical section. Time scale 20 s/cm, p_1 = 5 mm Hg, p_4 = 70 at m.

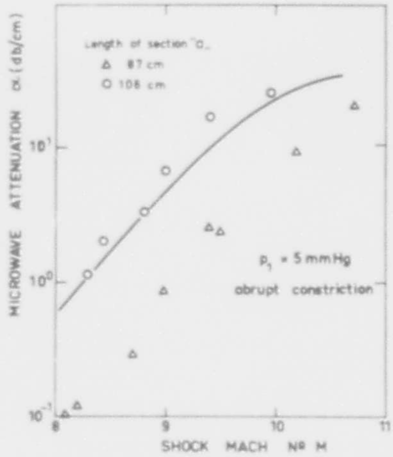

Fig. 10. Peak microwave attenuation as a function of Mach No. for the abrupt constriction. The Mach No. is changed by using different high pressure p_4. The points refer to the peak (1). The solid curve is the peak attenuation taken from the experimental values of Fig. 2.

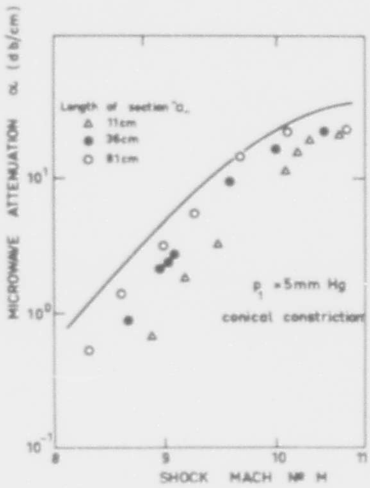

Fig. 11. Peak microwave attenuation as a function of Mach No. for the conical constriction. The Mach No. is changed by using different high pressures p_4. points refer to the first peak. The solid curve is that taken from the experimental values in Fig. 2.

DISCUSSION

Question by D. WALSH (U.K.) :

What fraction of the plasma is across the microwave system?

Answer by W. LOW (Israël) :

The space resolution is about 13 mm and this about 2-3 μs at the Mach number under consideration. The resolution is, therefore, better than the rise time to peak attenuation or the decay times.