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THE THICKNESS OF SHOCK AND DETONATION FRONTS AND ROTATIONAL RELAXATION AT HIGH TEMPERATURES

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SUMMARY

Optical reflectivity measurements of shock thickness in argon have been extended to much higher Mach numbers. Earlier shock thickness measurements at Mach numbers up to 1.55 were found to be in good agreement with Navier-Stokes theory. The present measurements show that this agreement becomes progressively less good as the Mach number increases. The shock thickness in argon appears to reach a maximum at about Mach = 3 on the basis of preliminary experiments conducted at M = 4.99 where the observed thickness agrees with the bimodal model of Muckenfuss.

The optical reflectivity method has also been applied to hydrogen-oxygen detonations and strong shock fronts in pure oxygen. These measurements suggest that rotational relaxation, which is known to be rapid at low temperatures, may become slow at high temperatures. It also appears that in detonation waves heating effects may extend into the region of the initial compression process.

I. Introduction

The optical reflectivity technique has made it possible in the past (1,2,3,6,7) to study the thickness of shock fronts at strengths up to $M = 1.55$ and in that region it was found that in argon thicknesses were in accord with the Navier-Stokes equations. In polyatomic gases it was possible to measure the contribution from the bulk viscosity and hence to determine apparent rotational relaxation times, 5.3 collisions being required to attain rotational equilibration in the case of nitrogen and fewer for heavier molecules. In the present studies measurements were extended to much stronger shocks and to detonation waves.

II. Experimental

The optical reflectivity method is based on the fact that light can be reflected from a shock front and that the reflectivity is a sensitive function of the density profile. It has been shown (3) that when $R \ll 1$, the reflectivity of a shock front is given by the expression

$$R(y) = \frac{1+\tan^4\theta}{4} \left| F(y) \right|^2 \tag{1}$$

where

$$F(y) = \int_{-\infty}^{\infty} \left(\frac{dn}{dx}\right) e^{-2\pi i x y} dx \tag{2}$$

and

$$y = 2\cos\theta/\lambda \tag{3}$$

Here θ is the angle of incidence, λ the wavelength of the radiation and n the index of refraction as a function of the distance x along an axis perpendicular to the shock front. The index of refraction is related to the density by the expression

$$\frac{\rho(x)}{\rho_o} = \frac{n(x)-1}{(n_o-1)} \tag{4}$$

where the o subscript refers to the reference state. If $R(y)$ could be measured over a sufficient range of y, $n(x)$ and hence $\rho(x)$ could be determined; in practice this is not possible and an analytic form with adjustable constants must be fitted to the data.

Until now we have used the function

$$n(x) = n_1 + \Delta n/1+e^{-4x/L} \qquad (5)$$

in which n_1 is the refractive index of the unshocked gas and L is a parameter measuring the shock thickness,

$$L = \frac{\Delta n}{\left(\frac{dn}{dx}\right)_{max.}} \qquad (6)$$

For this model the reflectivity is, from Eqs. (1) and (2)

$$R = \frac{1+\tan^4\theta}{4} (\Delta n)^2 \frac{(L\pi^2\cos\theta/\lambda)^2}{\sinh^2(\pi^2L\cos\theta/\lambda)} \qquad (7)$$

The function $\log R' = \log \dfrac{(\pi^2 L\cos\theta/\lambda)^2}{\sinh^2(\pi^2 L\cos\theta/\lambda)}$ is plotted in Fig. 1 as a function of $\log (\lambda/L \cos \theta)$.

This model (Eq. 5) is exact for the Navier-Stokes equations with constant coefficients as well as for the bimodal theory of Mott-Smith and Muckenfuss. It is a limiting case of the expression obtained from Sherman's solution of the Burnett equations, (11,12)

$$\frac{\rho}{\rho_1} = \frac{5 + \zeta}{5 - \zeta \tanh(2x/L)} \qquad (8)$$

where

$$\zeta = \frac{15(M^2-1)}{3+5M^2} \qquad (9)$$

when the shock strength parameter ζ is small.

The technique employed is to determine the value of the parameters (Δn) and L in Eq. (7) which gives the best fit to the experimental reflectivity function. It should be noted that although L is a "maximum slope thickenss", the method does not itself measure this quantity. It measures the best fit of a function of the form of Eq. (5) to the true density function.

The optical system employed in the present experiments is shown in Fig. 2.

Radiation from an Osram HBO.109 super pressure mercury arc lamp is collimated and impinges on the shock front as it passes the measuring station. A small fraction of the incident radiation, of the order of 10^{-5} to 10^{-8}, is reflected and passes successively through (a) the system iris which controls the area of the shock front seen by the detector, (b) a focussing lens, (c) an interference filter with a bandwidth of about 7 $m\mu$ and a peak wavelength of 436 $m\mu$ and (d) a slit which controls the divergence of the beam. It is finally brought to focus near the photomultiplier tube. The unreflected portion of the light passes through a similar interference filter and is received by a phototube whose output serves to monitor the intensity of the mercury lamp. In most of the experiments both λ and θ were kept constant and the reflectivity curve was scanned by varying the initial pressure, P_i, and hence L which is related to it by the scaling law

$$L_i P_i = L_o P_o \tag{10}$$

The apparatus was calibrated by measuring the reflection from weak shock waves in argon for which (Δn) was known from the expression

$$(\Delta n) = (n_o - 1)\, \frac{2(M^2-1)}{2+M^2(\gamma-1)} \left(\frac{\rho_1}{\rho_o}\right) \tag{11}$$

and L was known both from theory (5) and previous measurements. However the use of large values of $\lambda/L \cos\theta$ (Fig. 1) made the calibration reflectivity insensitive to the value of L used.

The accuracy and sensitivity of the method has been considerably improved over earlier measurements as a result of using the high intensity source, narrow band filters and of refining the optical system.

III. Shock Front Thicknesses in Argon

The results of recent measurements of the shock front thickness in Ar(8) are listed in Table I. Here σL_o is the estimated standard deviation of L_o, the thickness at an initial pressure of one atmosphere, l_o is the mean free path of the hard sphere gas having the same viscosity as Ar($l_o = 0.69 \times 10^{-5}$ cm at N.T.P.). The error limits are the 90°/o confidence levels. Fig. 3 shows a comparison of the experimental results with two theoretical curves. In the region of $M = 2.5$, the shock front thickness is about 25°/o greater than that predicted by the appropriate Navier-Stokes equation but agrees with the bimodal calculation of Muckenfuss (10). Also at $M = 4.99$ where data from preliminary measurements are reported, the experimental shock thickness is in agreement with that predicted by the bimodal calculation.

IV. Detonation Fronts

According to the accepted model of detonations, the reaction zone is preceded by a shock wave which heats and compresses the reactant gas. Subsequently the chemical reaction raises the temperature and consequently reduces the density. For the study of the initial shock wave the reflectivity method is particularly suited since its effective time resolution is of the order of 10^{-11}sec whereas the required resolution is estimated (4) to be only 10^{-8} sec. (the time elapsing before the chemical reaction sets in).

Distinguishing the reflected radiation from that due to the luminous gases behind the shock front was the prime difficulty in applying the optical reflectivity technique to the study of detonation fronts. This problem was overcome by the improvements previously mentioned, as well as by measuring radiation reflected from the back of the shock front so that the viewing system did not "see" into the reaction products. Furthermore, it was found that the luminosity increased as the first power of the initial downstream pressure whereas the reflectivity increases somewhat faster than the square. Thus the interference from gas luminosity could be reduced by working at higher initial downstream pressures. In practice it was found possible to make measurements at initial pressures down to 10 p.s.i.a. Finally, the luminosity was reduced by adding diluent gases which reduced the temperature behind the detonation wave.

The first detonation experiments were conducted with a $H_2:3O_2$ gas mixture (9). The important results of this work were:

1. the detonation front could be regarded as an optical surface for which the angular dispersion was less than 0.05 radian,
2. the detonation front thickness (9×10^{-5} cm at $M=4.6$) differed very slightly from shock front thicknesses usually found, and
3. the apparent density change ($\frac{\Delta\rho}{\rho_1} = 2.6$) was only 74°/o of that expected if the gas achieved equilibrium behind the shock front ($\frac{\Delta\rho}{\rho_1} = 3.5$). On the other hand it was not far from that expected if there was no rotational contribution to the heat capacity of the oxygen ($\Delta\rho/\rho_1 = 2.4$), i.e., if rotational relaxation were slow.

The preceding result led us to consider the following possibilities:

a. that there was little rotational excitation of O_2 in the shock front, and that about 20°/o of the equilibrium rotational energy was transferred in the shock front for which the temperature reached was about 1900°K. Equilibration would therefore require more than 100 collisions for O_2,

b. that heat flux into the shock front reduced the density change, perhaps giving a profile resembling that shown in Fig. 4 in which case the theoretical reflectivity curve of Fig. 2 would be inapplicable, and

c. that an unlocated experimental error was responsible.

To check these possibilities, experiments were conducted with the gas mixture $2H_2:O_2:10Ar$ for which rotational relaxation would have little effect. For this mixture, $\Delta\rho/\rho_1$ = 2.50 with no rotational heat capacity whereas with rotational equilibrium for O_2 only, $\frac{\Delta\rho}{\rho_1}$ = 2.61. The results obtained are shown in Fig. 5. It is clear that no curve drawn through these points can be superimposed on the theoretical reflectivity curve of Fig. 2. These results are evidence for supporting the second consideration but do not discredit the first. The decrease in R' at the highest initial pressures suggests that the density reaches a maximum and begins to fall within distances comparable to the thickness of the shock front.

V. Shock Thickness and Rotational Relaxation in O_2

As a further check on the hypothesis that rotational relaxation was slow in oxygen at high temperatures, preliminary measurements (9) were conducted on shock waves at M = 3.1 in oxygen for which the equilibrium temperature would be 834°K. The shocks were excited by detonating acetylene-oxygen mixtures in the driver section of the shock tube. These measurements yielded an apparent shock front thickness, L_o, of approximately 3×10^{-5} cm and a $\Delta\rho/\rho_1$ of $2.4+0.2$. The latter quantity would be 1.9 if there were no rotational excitation and 2.9 if rotational equilibrium were achieved. Consequently there appears to be roughly 70°/o rotational excitation in the shock front. More accurate measurements of rotational relaxation in this and other diatomic gases are being carried out.

VI. Conclusions.

It has now been possible to achieve reasonable precision in the measurement of the thickness of shock fronts. The thickness in argon reaches a minimum at about M=3 and at M=4.99 is in agreement with that predicted by the bimodal theory of Muckenfuss. Measurements on hydrogen-oxygen detonations as well as on strong shock fronts in pure oxygen suggest that whereas rotational relaxation is known to be rapid at low temperatures it may become slow at high temperatures.

Finally, it appears that in detonation waves heating effects may extend into the region of the initial compression process.

Acknowledgments

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Table 1

Shock Front Thickness in Argon

M	No. Runs	No. Calibrations	$L_o \times 10^5$cm	l_o	l_o/L_o
1.26	4	10	8.4±0.4	3.0%	0.082±0.004
1.33	1	5	7.0±0.4	4.0%	0.099±0.006
1.51	3	5	5.1±0.4	4.5%	0.137±0.010
2.38	43	50	3.0±0.1	2.0%	0.234±0.007
4.99	9	7	3.1±0.3	5.1%	0.225±0.019

Theoretical Reflectivity

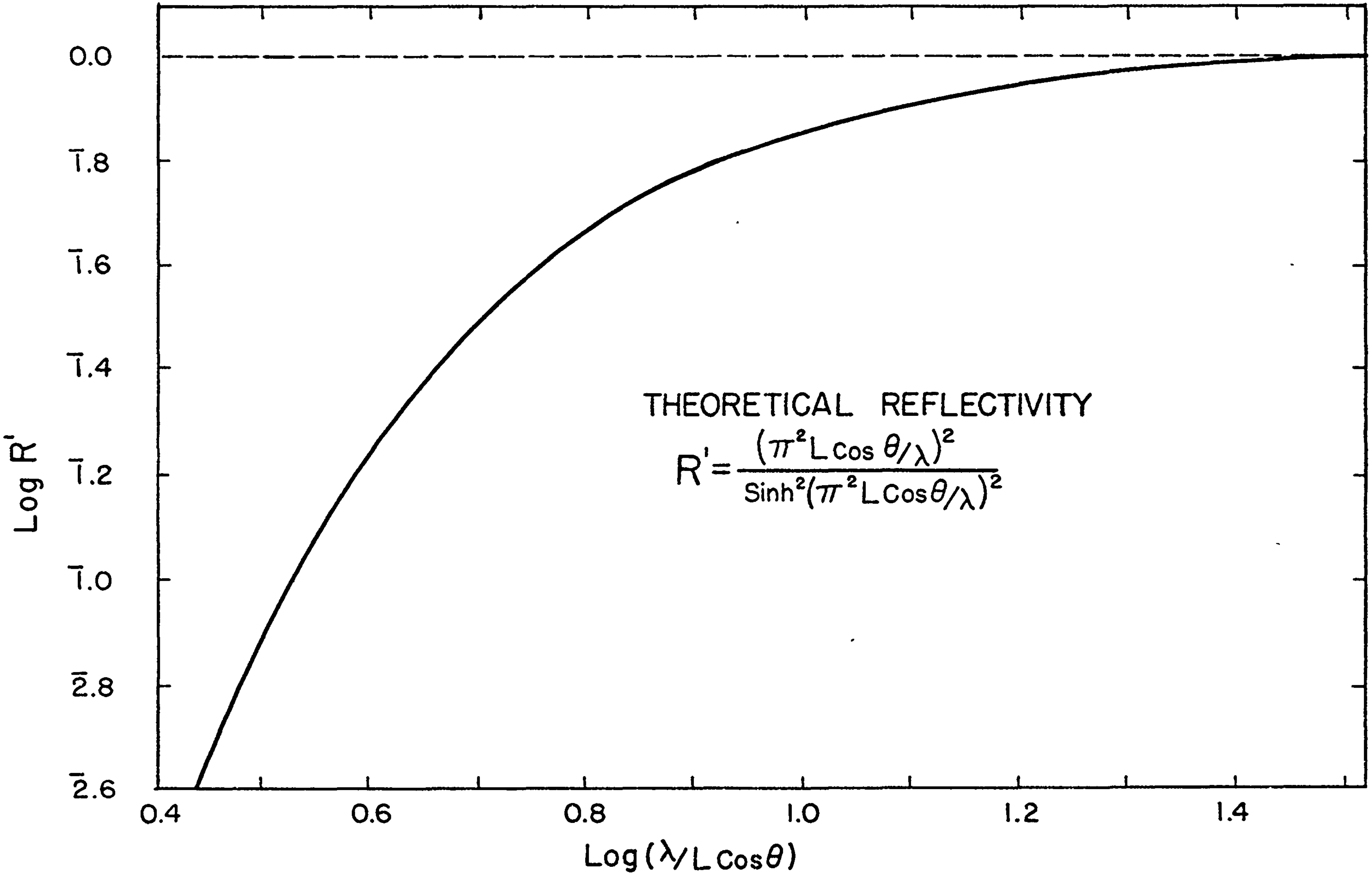
THEORETICAL REFLECTIVITY
$R' = \frac{(\pi^2 L \cos \theta/\lambda)^2}{\sinh^2(\pi^2 L \cos\theta/\lambda)^2}$
Log R'
0.0
$\bar{1}.8$
$\bar{1}.6$
$\bar{1}.4$
$\bar{1}.2$
$\bar{1}.0$
$\bar{2}.8$
$\bar{2}.6$
0.4
0.6
0.8
1.0
1.2
1.4
$\text{Log}(\lambda/L\cos\theta)$

FIGURE 1

Optical System

OPTICAL SYSTEM

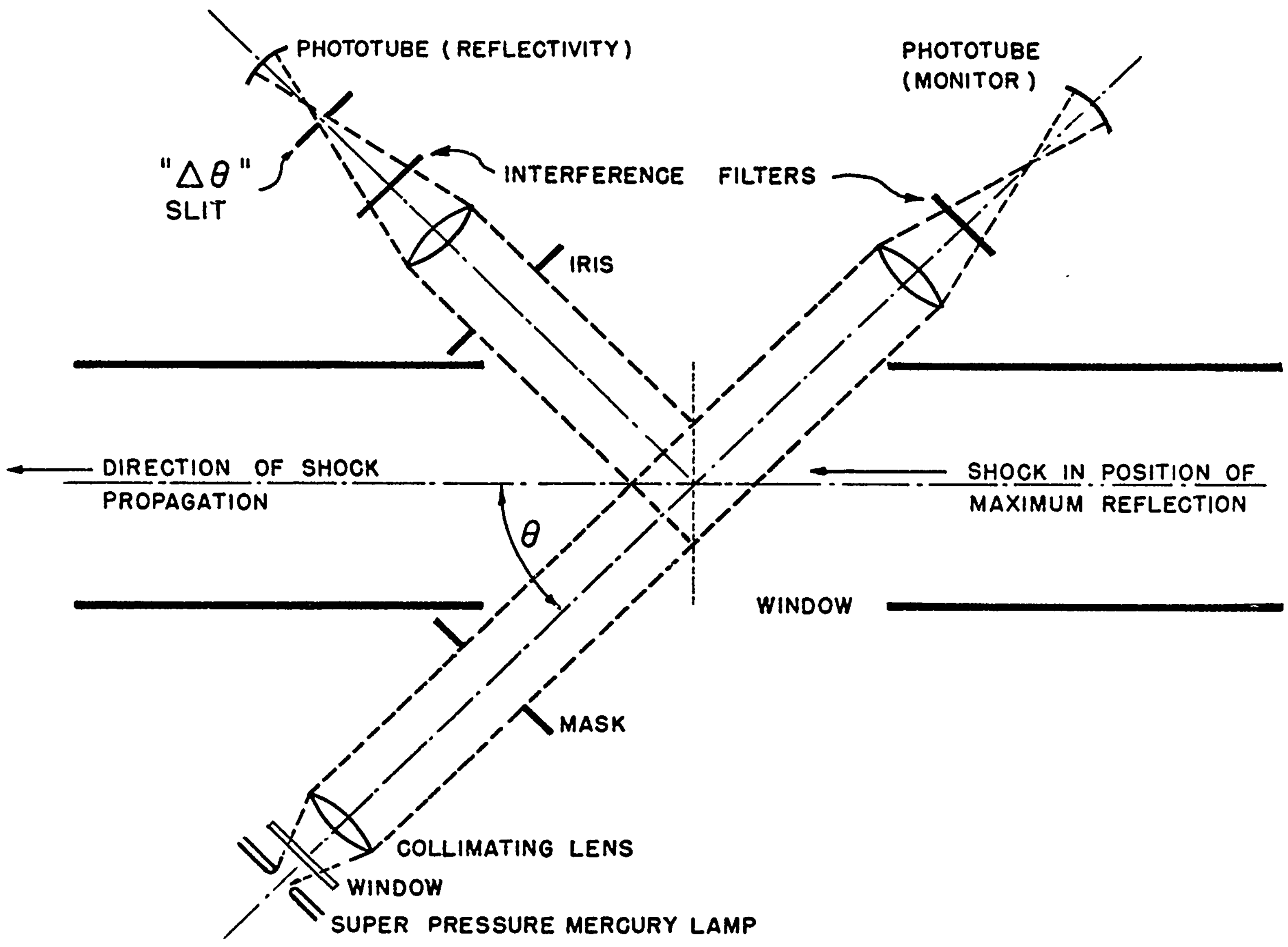

FIGURE 2

Reciprocal Shock Thickness (Mean Free Paths) versus Mach Number

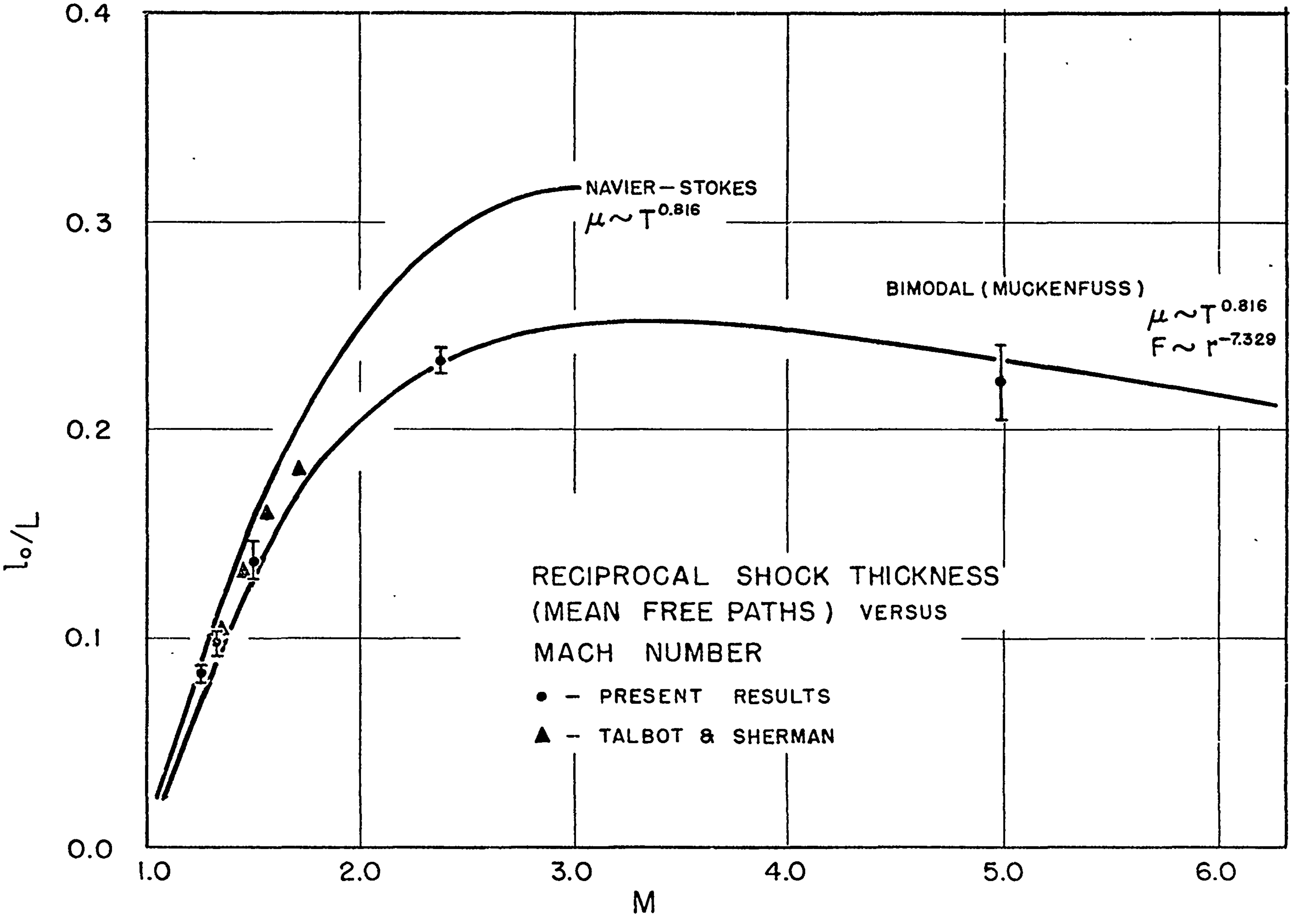
0.4
0.3
0.2
0.1
0.0
l_o/L
1.0
2.0
3.0
4.0
5.0
6.0
M
NAVIER – STOKES
$\mu \sim T^{0.816}$
BIMODAL (MUCKENFUSS)
$\mu \sim T^{0.816}$
$F \sim r^{-7.329}$
RECIPROCAL SHOCK THICKNESS
(MEAN FREE PATHS) VERSUS
MACH NUMBER
● – PRESENT RESULTS
▲ – TALBOT & SHERMAN

FIGURE 3

Detonation Front Density Profile

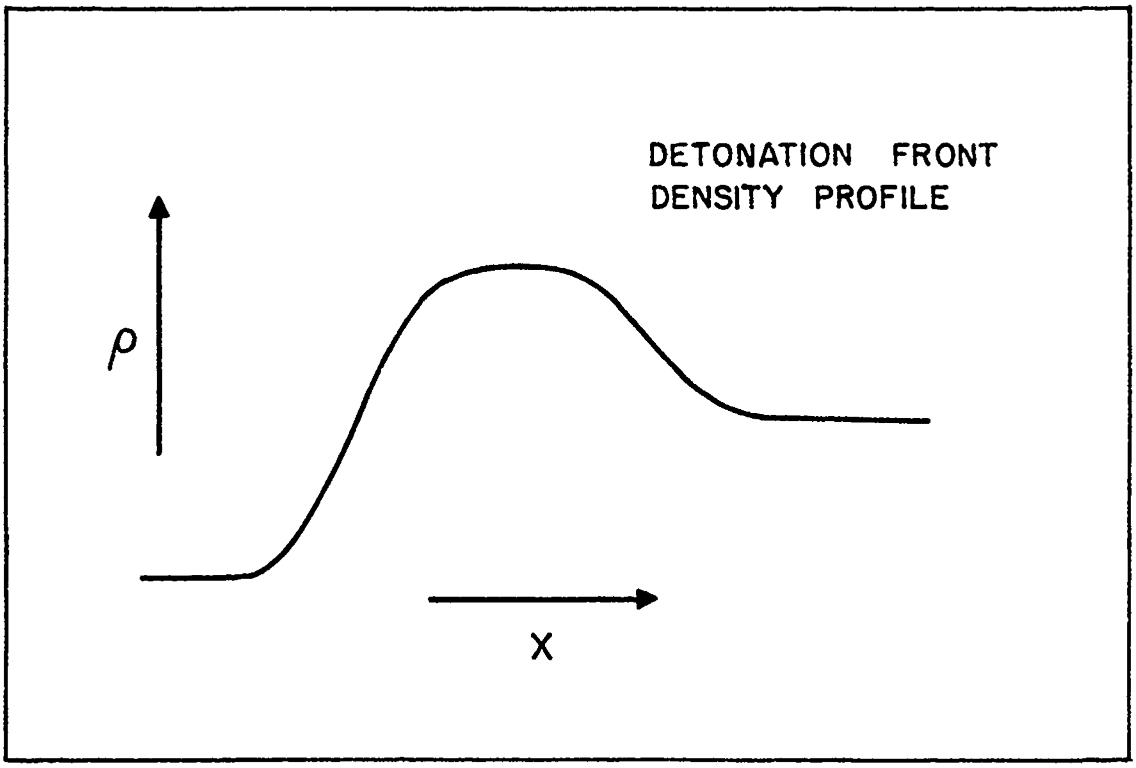

FIGURE 4

Experimental Reflectivities

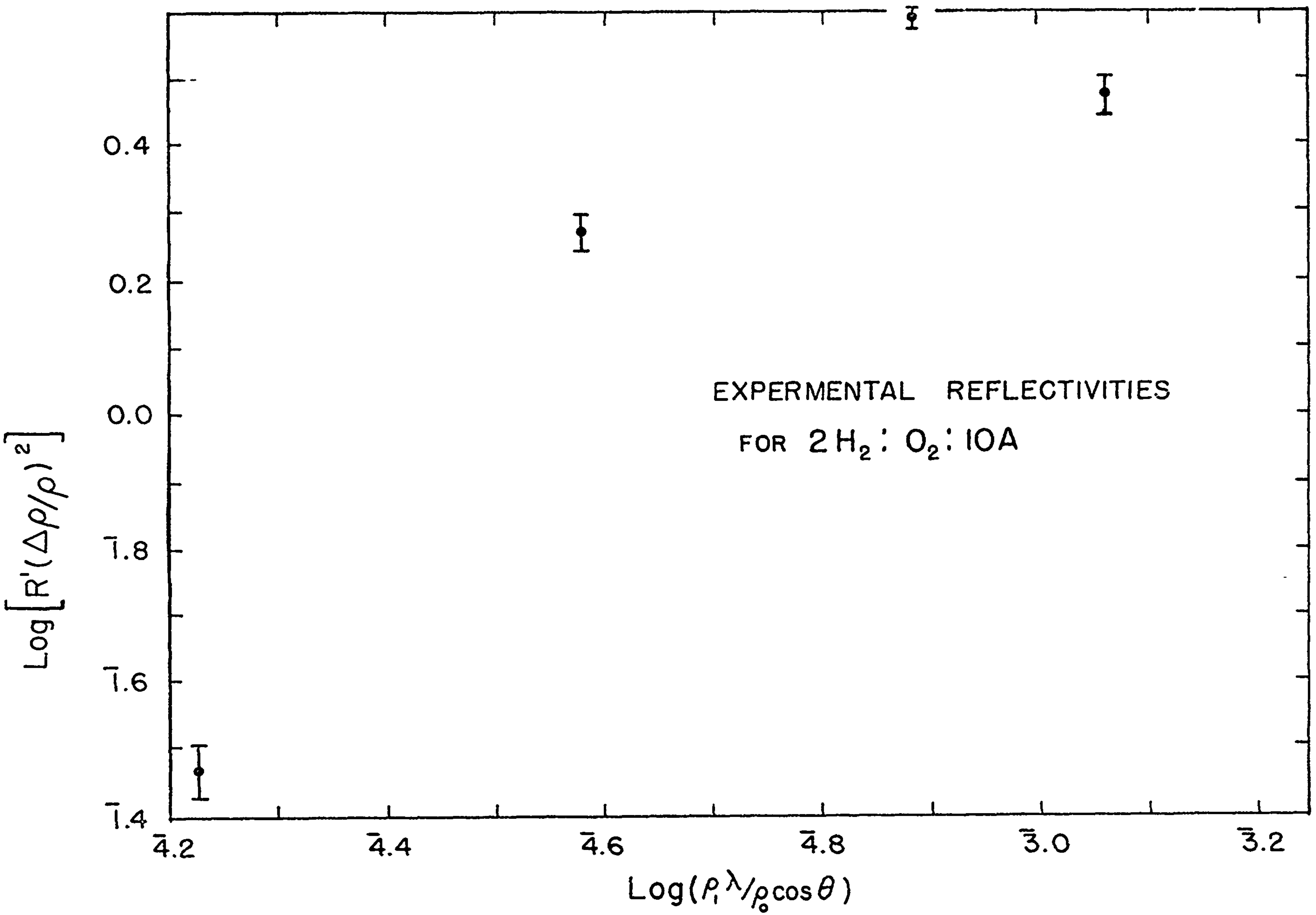
EXPERMENTAL REFLECTIVITIES
FOR $2H_2 : O_2 : 10A$
$\text{Log}\left[R'(\Delta\rho/\rho)^2\right]$
0.4
0.2
0.0
$\bar{1}.8$
$\bar{1}.6$
$\bar{1}.4$
$\bar{4}.2$
$\bar{4}.4$
$\bar{4}.6$
$\bar{4}.8$
$\bar{3}.0$
$\bar{3}.2$
$\text{Log}(\rho_1 \lambda / \rho_0 \cos\theta)$

FIGURE 5