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AN OPTICAL METHOD FOR DETERMINING ELECTRON AND ATOM DENSITY GRADIENTS APPLIED TO THE SHOCK REFLECTION PROBLEM IN A SHOCK TUBE

A.C.B. Hutten Mansfeld, E.J.M. van Heesch, M.E.H. van Dongen, G. Vossers. Department of Physics, Eindhoven University of Technology, Eindhoven, The Netherlands.

Abstract
A quantitative two wave length laser schlieren method is introduced as a means for determining electron and atom density gradients. It is applied to the ionized thermal boundary layer and relaxation zone that develop after shock wave reflection in a shock tube. The conditions considered here are, Machnumber: 6-10; initial pressure: 5 torr; distance from the endwall: 1.4 mm; testgas: argon. A typical result is shown.

INTRODUCTION

An ionizing shock wave, that reflects from the solid endwall of a shock tube causes the complicated one-dimensional, time dependent situation that is illustrated in fig.1. Behind the incident shock wave (region 2) there is a steady relaxation zone (2F) with a characteristic time $\tau 2$. In the first phase after reflection there is a nearly constant region of stagnant, "frozen" (F) argon between the reflected shock wave and the wall. After a relaxation time $\tau 5$ the ionization reaction in the reflected shock region (region 5) starts quite abruptly and leaves behind a new stagnant region of equilibrium (E) partially ionized argon (2F5E). Because of the fact that the relaxation time $\tau 5 << \tau 2$ due to the noticeably different conditions, it is possible to neglect the gasdynamical phenomena caused by the interaction of the incident relaxation zone and the reflected shock wave. The endwall cools the gas in its vicinity. This results into the formation of a thermal boundary layer (T.B.L.). The structure of the T.B.L. is very strongly influenced by the conditions of its outer region. Therefore some time after $\tau 5$ this structure is determined by the region 2F5E. Within this very thin T.B.L., of about 1 mm thickness, the heavy particle temperature will decrease from its 2F5E value to the wall temperature. Because of differences in transport properties between electrons and heavy particles, recombination processes and plasma-wall interaction phenomena, it is to be expected that the electron temperature will differ from that of the heavy particles.
From the T.B.L. experiments that have been done in the past to determine its time dependent structure we mention here the work of refs. (1-3); from the relaxation zone experiments, among others, refs. (3-4). Especially for the T.B.L. there remains a strong need for further and more accurate experimental information.

EXPERIMENTAL TECHNIQUE

Optical methods are advantageous for not disturbing the phenomena gasdynamically. We have chosen for a two wave length laser schlieren device for several reasons:

(i) it is sensitive only for variations perpendicular to the direction of propagation of the light beam; therefore side-wall effects are negligible;
(ii) it is relatively easy to obtain direct quantitative results;
(iii) the well defined Gaussian intensity distribution of the laser beam makes a higher order analysis possible and simplifies the data reduction;
(iv) because of the finite size of the beam, wall diffraction effects can be avoided;
(v) the sensitivity of the system can be chosen by adjusting the beam divergence, though this has consequences for the spatial resolution;

The basic idea is that a light beam is deflected in a non-homogeneous refractive index (N) field. In first approximation the angle of deflection is proportional to the gradient of N at the central axis of the beam. The refractive index of an ionized gas, $N = N(\lambda, n_e, n_a)$, is strongly dependent on the light frequency (ref.5). By using two different wave lengths, λ_1 and λ_2 it is possible to obtain both the gradients of the electron number density n_e and atom number density n_a. It can be shown that when using a laser beam the effects of higher order derivatives can be minimised by focussing the beam on the shock tube axis.

EXPERIMENTAL SET UP

In fig.2. a schematic view has been given of the endwall section of the shock tube and the optical arrangements. Both laser beams are adjusted in the same plane parallel to the endwall. The beam deviation is measured by the aid of a metal, reflecting, splitting prism. A non-homogeneity like the T.B.L. will cause a difference between the two signals which is a unique measure for the deflection angle.
The shock tube was made of extruded aluminium. The impurity level due to outgassing was less than 10 p.p.m.

EXPERIMENTAL RESULTS

A typical result is presented in fig.3. Initially we see the signal peaks due to the passage of incident and reflected shock waves. Then the relaxation phenomena are clearly observable, followed by a signal increase caused by the non-stationary T.B.L. gradients. From the records an estimate can be made of the relaxation time $\tau 5$, which is in good agreement with values measured by ref.(3) interferometrically. In fig. 4. the electron and atom density gradients calculated on the basis of the signals of fig. 3. are depicted.

CONCLUDING REMARKS

The first experiments with the two wave length laser schlieren system appear to be promising. At present measurements are being carried out at different distances from the endwall. To improve the accuracy of the data analysis, displacement and distortion corrections will be applied. It is to be mentioned that this method is especially suitable for quantitatively determining the T.B.L. structure in its outer part.
A numerical solution for the equations describing a two-temperature T.B.L. model is well under way; the results of which will be presented elsewhere.

References
1: Camac, M., R.M. Feinberg, J. Fluid Mech. 21 (1965) 673
2: Knöös, S., J. Plasma Physics 2 (1968) 243
3: Kuiper, R., SUDAAR rep.no. 353, Stanford Univ. (1968)
4: Smith, J., Phys. of Fluids 11 (1968) 2150
5: Alpher, R.A., D.R. White, Phys. of Fluids 2 (1959) 153

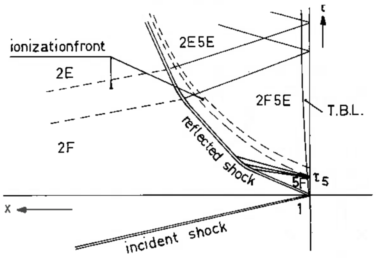

Fig.1 Schematic (x,t) diagram of the shockreflection process with ionization. M=7.59; p_1=5 torr.Argon;
5F: T=12911 K; p=2.712 10^5 N/m^2;
2F5E: T=10411 K; p=2.541 10^5 N/m^2; α=0.020.

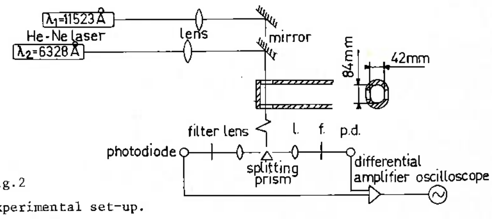

Fig.2
Experimental set-up.

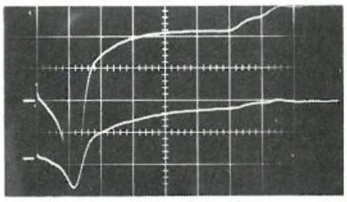

Fig.3
Beamdeviation as a function of time.
U.B.:λ_1 (50μsec/div.)
L.B.:λ_2 (50μsec/div.)

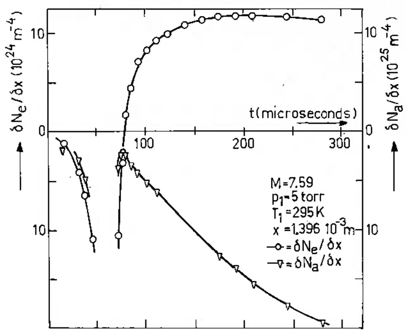

Fig.4
Atom and electron density gradients as a function of time after shock-wave reflection.