Shock Tube Boundary Layers in Ionized Argon-Helium Mixtures

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Nomenclature

C = viscosity density ratio = $\rho\mu/\rho_w\mu_w$
h = specific enthalpy = $(5/2\bar{m})KT(1+\alpha)+\alpha\chi$
K = Boltzman's constant
$\bar{m}$ = mass of mixture
Pr = equilibrium Prandtl number, based on equilibrium properties
T = temperature
y = normal distance from plate
α = degree of ionization
δ = boundary-layer thickness
χ = ionization potential, i.e., energy necessary to ionize an argon atom
ρ = heavy particle density
μ = viscosity
Subscripts
e = main stream value
w = wall value

Introduction

EXPERIMENTALLY, the boundary layer behind the primary shock in a shock tube has not been studied for the case of ionized gases. Previously, Mirels[1] has analytically studied the laminar boundary layer in equilibrium with constant Prandtl number and with a viscosity-density variation for equilibrium air. Also, Kemp and Moh[2] have studied both the frozen and equilibrium cases for nitrogen. The purpose of this short note is to outline a study that was made of the boundary layer behind a primary shock in a shock tube where the gas was an ionized argon-helium mixture and the Mach number approximately 18. Experimentally, two laser interferometers were used in conjunction with a photo diode and STL camera. Analytically, an equilibrium boundary layer was assumed and the Prandtl number and viscosity density ratio were allowed to vary. Ionization was taken into account in the boundary-layer equations and in calculating transport properties. The particular region of the gas sample studied extended from the beginning of recombination to the contact surface.

Experiment

The arc-driven shock tube had a 15 cm bore and for a 3-m length was bisected by a smooth flat plate tightly fitted to the walls. The flow studied was far enough from the leading edge of the plate so that the particles accumulated preceding the leading edge were no longer in the sample. The flow was analyzed using two interferometers of the Twyman-Green type.[3] They were placed at the same axial position but at different heights above the plate. One interferometer had a large beam approximately one cm in diameter and traversed the boundary-layer region. The other interferometer had a small beam approximately 1 mm in diameter and traversed the mainstream away from the boundary layer. The mainstream interferometer has been discussed in Ref. 3. The boundary layer interferometer was of the same type, except a pulsed argon laser was the light source and the STL image converter camera operating in the framing mode was the detector. The framing pictures of the boundary layer were taken in the recombination region where thermal equilibrium is assumed.

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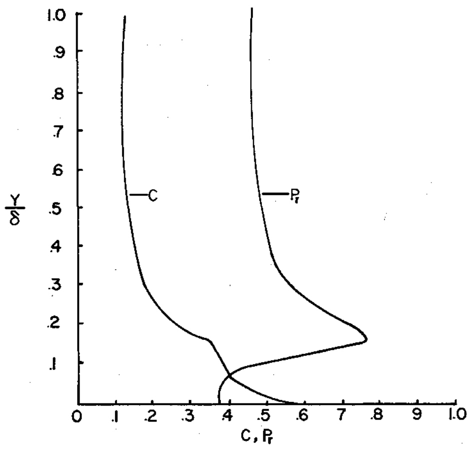

Fig. 1 Equilibrium Prandtl number and viscosity-density ratio profiles in the boundary layer.

Analysis

A. *Experimental data*

The fringe shift equation relating electron and neutral density is given in Ref. 3. This relation, along with the equations of mass, momentum, energy, state and the Saha equation were solved for conditions before the shock and at the beginning of recombination. Using the same conservation equations, but allowing for energy loss due to radiation, the mainstream conditions at each of the framing picture locations were determined.

Applying the fringe shift relation to the boundary-layer data and using the equation of state and the Saha relation, properties in the boundary layer were computed.

B. *Boundary-layer theory*

A form of local similarity was used in the boundary-layer analysis. Local similarity means that the boundary layer acts locally as if it existed behind a shock wave with the actual shock velocity, but that the mainstream properties throughout the sample are constant and equivalent to local values. This eliminates the pressure gradient terms in the boundary-layer equations.

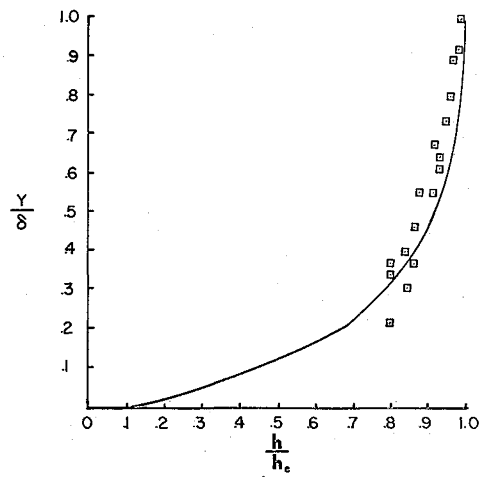

Fig. 2 Electron density profiles in the boundary layer (plotted points are experiment values).

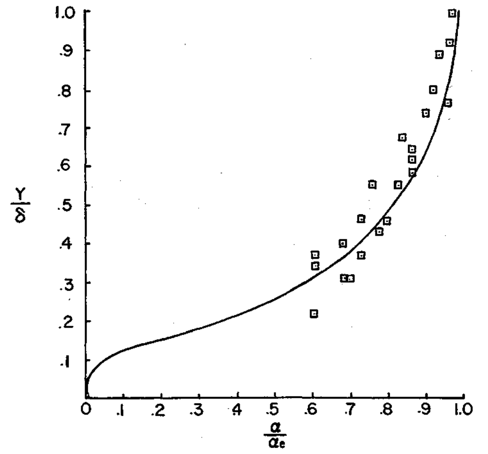

Fig. 3 Enthalpy profiles in the boundary layer (plotted points are experimental values).

The resulting equations for the equilibrium case are presented in Ref. 1 in the form of the familiar similarity variables. These require knowledge of the viscosity-density ratio and equilibrium Prandtl number in the boundary layer. In calculating the transport properties, the correlations given in Amdur and Mason[4] for a two-component mixture were used for viscosity and thermal conductivity. The viscosity and conductivity of helium was taken from Amdur and Mason.[4] The viscosity of argon was taken from Aeschliman[5] and Cambel.[6] The thermal conductivity of argon was taken from Ambur and Mason[4] below 5000°K and Knopp and Cambel[7] above 5000°K, The equilibrium specific heat was computed by an equation given by Cambel.[6]

The energy and momentum equations were put in integral form. The viscosity-density ratio and equilibrium Prandtl number were initially assumed unity. Then the momentum and energy equations were solved for the specific enthalpy distribution. The temperature, heavy particle density and electron density were determined from the Saha equation and the equation of state. Transport properties, viscosity-density ratio and the Prandtl number were computed and the process repeated until convergence.

Results

Figure 1 shows a typical variation of the equilibrium Prandtl number, Pr, and viscosity-density ratio, C, across the boundary layer. The ordinate on the boundary-layer plots is the dimensionless distance y/δ where δ is the boundary-layer thickness defined here to be the position where $h/h_e = 0.99$.

The results of Fig. 1 are interesting for two reasons. First, it is sometimes assumed that the viscosity-density ratio and equilibrium Prandtl number are equal to unity and constant across the boundary layer. This is clearly not the case. Secondly, it is apparently ionization that produces the abrupt changes in the properties.

Figures 2 and 3 show boundary-layer properties for a typical case. Experimental data are plotted with the theory. Curves for other properties show similar behavior. In all cases there is good agreement between the theory and the data, except close to the surface where frozen conditions may prevail. The unusual shape of the electron density profile in Fig. 3 is because of the cold wall. In the region where the data were taken, the temperature and density profile change very little compared to the other two profiles. Changes in enthalpy in Fig. 2 are therefore due to changes in electron density.

Conclusions

Assuming an equilibrium laminar boundary layer and using a form of local similarity theoretical property profiles agree favorable with the experimental data. Thus, it appears that the boundary layer in the recombination region behind primary shocks is laminar in nature and primarily in equilibrium, even at these high Mach numbers (~ 18) and with ionized gases. Boundary-layer studies behind shocks of this high strength have never been made. However, Hartunian et al.[8] indicated that perhaps the cool wall stabilized the boundary layer. They found for $T_w/T_e < 0.2$ the boundary layer was always laminar. Here $T_w/T_e = 0.02$, so this gives some credence to their statement. Very close to the surface there is perhaps a region where the flow is frozen.

The present interferometer was incapable of very close measurements. Further refinements in instrumentation are needed and should be carried out.

In addition, the effect of ionization has been shown on the viscosity-density ratio and the equilibrium Prandtl number. Previously, the temperature variations of transport properties for agon at one atmosphere have been computed (see, for example, Penski[9]). Here, and argon-helium mixture is considered and included in the boundary-layer theory.

References

[1] Mirels, H., "Laminar Boundary Layer Behind a Strong Shock Moving into Air," TN-D-291, 1961, NASA.

[2] Kemp, N. H. and Moh, T. C., "Laminar Boundary Layer Behind a Very Strong Shock Moving into Nitrogen," *Proceedings of the 5th International Shock Tube Symposium*. 1965, pp. 1013–1020.

[3] Besse, A. L. and Kelley, J. G., "Interferometer for Shock Tube," *Review of Scientific Instruments*, Vol. 37, 1966, pp. 1497–1499.

[4] Amdur, I. and Mason, E. A., "Properties of Gases at Very High Temperatures," *The Physics of Fluids*. Vol. 1, 1958, No. 5, pp. 370–383.

[5] Aeschliman, D. P., "An Experimental Determination of the Dynamic Viscosity of Atmospheric Argon from 3500 to 8500 Degrees Kelvin," NU-GDL Rept. B-1-68, March 1968, Northwestern Univ., Evanston, Ill.

[6] Cambel, A. B., *Plasma Physics and Magnetofluid Mechanics*, McGraw-Hill, New York, 1963.

[7] Knopp, C. F. and Cambel, A. B., "Experimental Determination of the Thermal Conductivity of Atmospheric Argon Plasma," *The Physics of Fluids*, Vol. 9, No. 5, 1966, pp. 989–996.

[8] Hartunian, R. A., Russo, A. L., and Marrone, P. V., "Boundary Layer Transition and Heat Transfer in Shock Tubes," *Journal of the Acrospace Sciences*, Vol. 27, 1960, 00. 587–594.

[9] Penski, K., "Zustands- und Transportgrossen von Argon Plasma," *Chem. Ing-Techn.*, Vol. 34, 1962, pp. 84–87.

Use of an Infrared-Imaging Camera to Obtain Convective Heating Distributions

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As re-entry configurations become more sophisticated, the convective heating patterns on these configurations tend to become both more complex and more sensitive to freestream conditions. There is, therefore, a need to develop rapid and accurate wind-tunnel techniques to measure heating distributions. One such technique is described in the present Note. Its essence is the measurement of infrared emission from the surface of a wind-tunnel model as a function of time by means of an infrared-sensitive imaging camera. Prior calibration of the infrared camera relates the emission to the surface temperature of the model. The time history of the surface temperature can then be realted to the heating rate by standard techniques. The output

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