High Enthalpy Hypersonic Boundary-Layer Flow

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Theme

THE development of the free piston shock tube/tunnel by Stalker[1,2] has enabled the study of gas flows at much higher enthalpies than was previously possible. That is, the combustion driven shock tube can produce stagnation enthalpies of the order of about 3000 Cal/gm, while values of 7000–10,000 Cal/gm are not unusual with the free piston device.

This paper is a detailed theoretical and experimental study of 1) the properties of laminar boundary layers formed in very high enthalpy flows (in excess of 7000 Cal/gm or 12 eV) in an ionizing monatomic gas, and 2) the operation of the nozzle of a reflected shock tunnel with special attention being given to the effects of Helium driver gas contamination upon the flow characteristics. In the complete work previous literature is reviewed and two appendixes are also presented detailing the methods used to calculate the transport properties and the experimental procedures.

Contents

The aim of this work was to produce a theoretical and physical understanding of the flow and boundary-layer properties of a very high enthalpy, partially ionized real gas flow, sufficient to enable accurate predictions of the surface heat transfer rates to an inclined flat plate in the test section.

One aspect of the work was the detailed examination of the solutions to the equilibrium and chemically frozen real gas ionizing boundary-layer with variable transport properties and Prandtl number. As the solution proceeds from the plate surface to the freestream, the Prandtl number may have variations between the ideal value of 0.67 to very small values of the order of 0.07. The theory of Fay and Riddell[2] for a dissociating laminar boundary layer was modified to the case of an ionizing monatomic gas. The concept of similarity was used to solve the equations.

The inclusion of variable transport parameters and Prandtl number has a marked effect on the enthalpy in the boundary layer. The shape of the velocity profile produces a hot region well above the surface, but decreases the temperature gradient near and on the wall. The lowering of the wall temperature gradient will, in turn, produce a lower surface heat transfer rate. The higher the flow enthalpy, the greater will be these developments. Dramatic changes also appear in the profiles for other parameters of interest such as the ionization fraction and density. Figure 1 shows the transformed profiles of temperature, ionization fraction, and Prandtl number for a typical boundary layer.

Theoretical predictions were made of the freestream condition to be expected in the shock tunnel test section, especially those parameters which were eventually to be measured. The shock conservation equations for mass, momentum, and energy were solved simultaneously with the thermodynamic relations for the enthalpy, the state of the gas, and the Saha Equation, to determine the reflected shock conditions that act as the reservoir for the expansion nozzle feeding the test section. The nozzle flow was calculated under the assumption of equilibrium flow. Equations were developed for real gas pure argon flows, and real gas argon-helium mixtures. The problem of flow divergence was also considered, since the nozzle was of conical design. The emerging flow was considered a source-type starting at the throat of the nozzle. The two-dimensional flow problem over the inclined plate was solved in a straight-forward geometrical manner. The results of the nozzle exit calculations were, in turn, theoretically passed over various oblique shock fronts, produced by the inclined flat plate, again using real gas solutions. The calculation results include all the parameters that were to be measured in the experimental portion of the study, e.g., pitot pressure, density, and surface heat transfer rates. It should be noted that the shock angles used in the calculations were the values obtained experimentally using a Mach-Zehnder interferometer with one fringe spread out over the whole field of view.

The presence of helium in the flow lowers the degree of ionization throughout the boundary layer. At 4.76% helium by mass, the transport properties are modified sufficiently from the case of pure argon flow to produce a practically constant value of the Prandtl number across the whole of the boundary layer.

The final aspect of the work was the correlation of the experimental data with the theory. The concept of a "composite" boundary-layer solution was introduced as an approximation to the nonequilibrium solution. Experimental determinations were made for the test section pitot pressure, test section density via Mach Zehnder interferometry, and surface heat transfer rates on the inclined flat plate.

The pitot pressure dropped significantly at approximately 85 μsec after shock reflection. This observation received much careful study, and many possible explanations were examined. It was finally determined that this drop was a manifestation of shock boundary-layer interaction in the reflected shock region

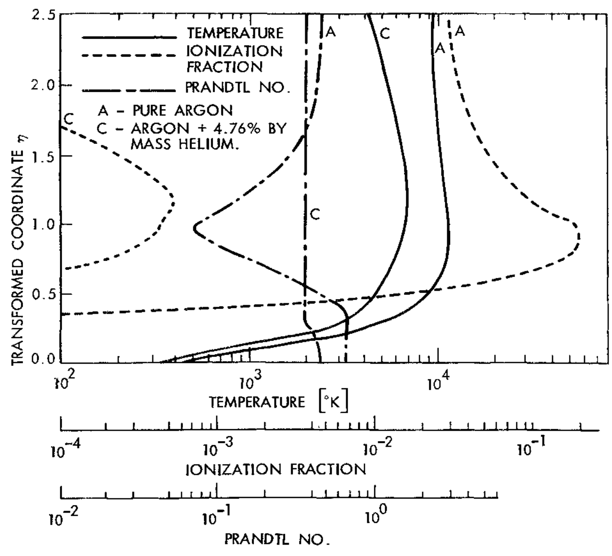

Fig. 1 Typical freestream conditions over the surface of the plate behind the oblique shock front, small exit nozzle.

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Index categories: Boundary Layers and Convective Heat Transfer—Laminar; Supersonic and Hypersonic Flow.

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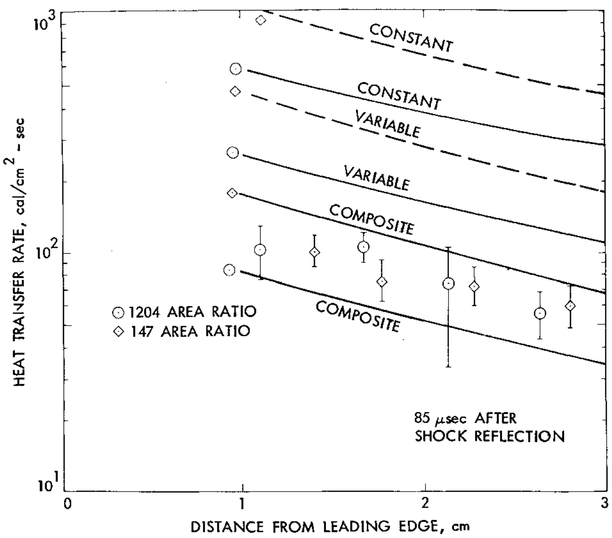

Fig. 2 Heat transfer rates. ◇ data and curves are for nozzle with area ratio of 147, 9.5° plate inclination. ⊙ data and curves for area ratio of 1204 and 19.5° plate inclination. The composite solution was obtained using a value for the matching criterion, I_c, of approximately 10.

ahead of the nozzle throat. It is hypothesized that relatively cold helium driver gas leaked along the side walls of the shock tube and reached the area of the throat. This contaminating gas fed into the periphery of the argon flow. The helium occupied a greater relative area in the throat than it did further down the nozzle due to the difference in the ratio of specific heat of this gas and the ionized argon; i.e., the ionization present in the argon lowered the effective gamma to a much lower value than that of the helium, which at all times remained a "perfect" gas. This dual flow in the nozzle increased the area that the argon experienced, and thereby caused the dramatic drop in the pitot pressure.†

The major experimental information used was surface heat transfer rates measured on the inclined flat plate. The heat transfer gages were the thin film type made by painting and firing a platinum solution into the surface of pyrex glass inserts. The gages were coated over with china paint, and each gage was individually calibrated for the rate of change of resistance with temperature and the bulk coefficients of thermal conductivity, density, and specific heat.

Figure 2 shows thermo-chemical equilibrium surface heat transfer rate predictions and measured values. The theoretical curves are shown for both the cases of constant and variable transport parameters and Prandtl number. The experimental data is for a period approximately 85 μsec after shock reflection. It should be noted that the points shown are the mean value of many determinations, using different gages at the same position on the plate with the same flow and tilt conditions. The flags are the standard deviation of the data. The composite prediction will be discussed below.

† It has recently been called to the authors attention that radiation loss in the reflected shock region could also contribute to the pitot pressure drop. The contamination via the cold Helium driver gas would also accelerate radiation losses by very rapidly cooling the periphery of the reflected shock heated slug of test gas.

The measurement at 1.1 cm distance up the plate from the leading edge probably suffered merged region effects. The variable Prandtl number markedly lowered the surface heat transfer rate. The large exit nozzle (1204 area ratio) predictions and measurements are close to a factor of 2 from one another, the limit set as acceptable, but the correlation of the small exit measurement and the theory was not close to being what was considered adequate.

The chemically frozen boundary-layer heat transfer predictions, with or without a catalytic surface, were higher than for a boundary layer in thermo-chemical equilibrium with variable Prandtl number. Analysis of the data showed the helium contamination would not improve the correlation between theory and measurement. Therefore, some other mechanism had to be found to account for the low heat transfer rates. The most likely item to account for this discrepancy was taken to be nonequilibrium flow over the plate.

A careful analysis of the mechanisms of ionization and recombination of argon suggested that the change in the character of the boundary layer from nearly frozen to nearly equilibrium might occur very rapidly. The term "nearly" is taken to mean the most correct mathematical description. Consequently, the very difficult problem of a full nonequilibrium solution might be approximated by simply matching together the frozen and equilibrium calculations. The criterion for matching the frozen solution of the upper portion of the boundary layer to equilibrium solution of the lower portion was based on an examination of the electron density, N_e, and the recombination rate, K_r, at some characteristic time of interest (85 μsec after shock reflection). The criterion where the solution was switched from a frozen integration to an equilibrium integration was taken as $I_c < N_e/N_e^3 K_r T_c$ where I_c was some arbitrary constant determined by an examination of the gradient of the recombination curve. This relation can be interpreted as meaning that if the number of electrons is greater than some factor times the possible number that could be recombined within the characteristic time, the gas is mathematically defined as frozen. The concept of similarity was also employed in the matching of the solutions.

The best correlation between theory and data was obtained when a matching layer was chosen where there was a strong tendency to depart from the frozen state. That is, the recombination was starting to become significant. Referring back to Fig. 2, it can be seen that in no instance for the composite solution is the difference between the predicted and measured heat transfer rates greater than a factor of 2. Indeed, the accuracy is much better than this generally, with the normalized standard deviation for all measurements from the composite theory being less than 40%.

The composite boundary-layer solution would seem to offer a reasonable alternative to the much more difficult nonequilibrium calculation in the cases of very high enthalpy flows. It may be of particular usefulness for engineering predictions.

References

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