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Laser Radiation—Gasdynamic Coupling in the SF_6-Air Laminar Boundary Layer

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Abstract

PRACTICAL problems arise where the shielding of aerodynamic surfaces from high-power laser beams is of importance. For example, a highly absorbing gas can be injected into the boundary layer of an airplane or missile in order to protect its surface materials from the incoming laser radiation. Initial work demonstrated that SF_6 is a very strong absorber[1,2] of CO_2 laser radiation. Therefore, this work deals solely with the radiative gasdynamic interaction associated with CO_2 laser radiation absorption in a SF_6-air laminar compressible boundary layer. However, the implicit finite difference technique employed is applicable to any arbitrary laser wavelength provided an absorption coefficient for the associated absorbing gas is known as a function of pressure and temperature.

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This work extends earlier flat plate results[3] to include the stagnation point and downstream region of an axisymmetric body. The explicit numerical scheme used in the flat plate results required initial guesses for the unknown derivatives at the wall (standard shooting point technique) to be correct to within six or seven significant figures before the solution would begin to converge. Therefore, this explicit scheme was replaced with a more efficient implicit numerical scheme[4] which does not have these stability difficulties.

The boundary-layer equations (laminar, nonlinear, partial differential equations) are solved with mass injection rate of SF_6 and incoming CO_2 laser radiation. A self-similar solution is employed at the stagnation point to obtain an initial profile as input to the implicit finite difference solution for the nonsimilar region downstream of the stagnation point. The laser beam is of uniform intensity and parallel to the flow direction. As the laser beam is attenuated, the temperature in the boundary layer increases which in turn affects the absorption coefficient of the gas. Therefore, the radiative transport equation is fully coupled to the fluid mechanic boundary-layer equations.

In the present analysis, the gas absorbs but does not emit. The radiation that reaches the wall is totally absorbed by the wall and not reflected back into the boundary layer. The translational, rotational, and vibrational energies of the absorbing gas are in thermal equilibrium. Profile variations across the boundary layer are considered in velocity, temperature, air and SF_6 species concentration, and laser intensity.

The boundary-layer equations for two-dimensional or axisymmetric, multicomponent chemically nonreacting flow and the radiative transport equation[5] are transformed using the Mangler and Howarth-Dorodnitsyn transformation and then numerically integrated using the Crank-Nicolson scheme.[4] Variable mixture transport properties of viscosity, conductivity, specific heat (including vibrational excitation), binary diffusion coefficient, and radiative absorption coefficient for the air-SF_6 mixture[5] are included.

A rather extensive study of the absorption coefficient as a function of pressure, temperature, and species concentration was obtained experimentally by the authors[1,2] for near-atmospheric pressures and the elevated temperatures pertinent to the present aerodynamic application.

The wall boundary conditions of no slip, known temperature, and known mass injection rate of SF_6 were used along with the wall being impermeable to air. The velocity, mass fraction of air, and temperature at the outer edge of the boundary layer are specified from the inviscid flow problem and the edge radiative intensity is given.

Stagnation point and downstream solutions[5] have been obtained which show the effect of mass injection rate of SF_6, intensity of the laser radiation at the edge of the boundary layer, Mach number, and radius of curvature on the fluid mechanic variables and boundary-layer parameters.

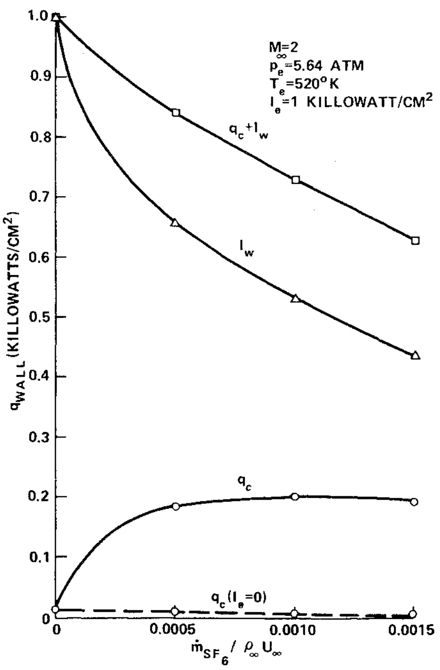

Fig. 1 Wall heat transfer vs mass injection rate.

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Index categories: Radiation and Radiative Heat Transfer; Lasers.

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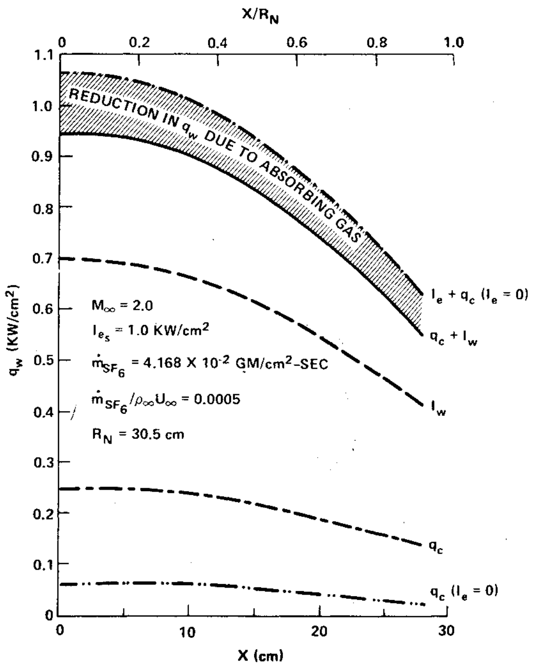

Fig. 2 Wall heat transfer for $M_\infty = 2.0$ flow over a sphere.

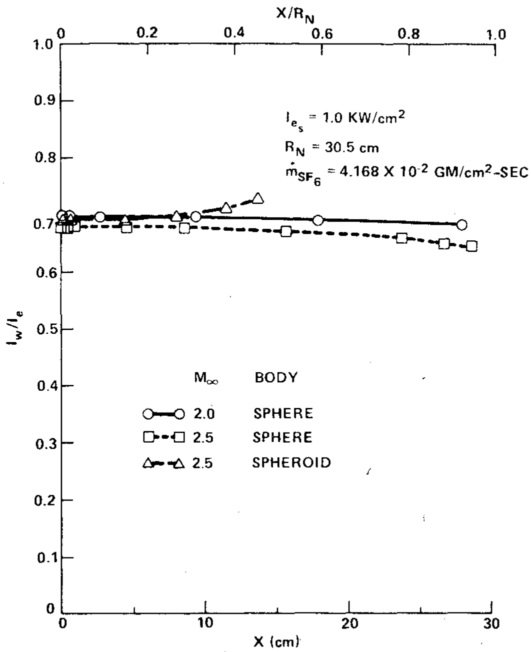

Fig. 3 Comparison of laser radiation reaching the wall, I_w/I_e.

Strong fluid mechanic coupling with the laser radiation is evident in that the gas temperature increases rapidly in the region of large radiative absorption. The velocity profiles overshoot to where the velocity within the boundary layer is larger than that of the freestream velocity. As the gas heats up the absorption coefficient decreases rapidly with the increasing temperature. The net reduction in the laser intensity and total heat transfer that reaches the wall is therefore lower than initially anticipated.

As the mass injection of SF_6 is increased, the total heat transfer at the wall (convective heat transfer q_c, plus laser radiative intensity I_w) and the laser radiation reaching the wall I_w decrease as shown in Fig. 1. The net reduction in radiation is seen to be large considering the small values of the SF_6 injection rate required.

One purpose of this particular study is to characterize the influence of the fluid mechanic expansion around a blunt body on the laser radiation absorption process. The expansion process lowers the temperature within the boundary layer and, consequently, more laser radiation absorption can occur.

In terms of heat transfer at the body surface a coupling exists between the convective mode of heat transfer q_{cw} and the radiative mode of heat transfer I_w. A decrease in the magnitude of the laser intensity that reaches the wall implies that greater absorption occurred within the boundary layer. This increased absorption causes the temperature to rise within the boundary layer. The higher temperatures result in increased convective heat transfer. The net heat transfer to the wall, therefore, depends on this combined, "coupled" effect.

The various contributions to the heat transfer at the wall are shown in Fig. 2 for a Mach number of 2.0 flow over a sphere of radius 30.5 cm. The boundary conditions are a constant wall temperature of 300 K, an SF_6 mass injection rate of 0.05% of the freestream mass flow, and a laser intensity of 1.0 kW/cm². The shaded region shows the reduction in heat transfer due to the absorbing gas. Note that q_c ($I_e = 0$) represents the convective heat transfer rate that would have existed if there were no radiation present.

The laser intensity reaching the wall I_w decreases with increasing distance around the body x, however, this decrease is primarily due to the magnitude of the laser intensity at the edge decreasing (cosine variation due to head-on laser assumption) rather than a result of increased absorption due to the temperature decreasing around the body. This is demonstrated in Fig. 3 by plotting I_w/I_e and observing a small increase in this parameter. An elliptical and spherical body at a Mach number of 2.5 are also shown in Fig. 3, showing a slight decrease in I_w/I_e.

Therefore, the downstream expansion around the body is shown to be relatively ineffective for enhancing the SF_6 absorption process of the CO_2 laser radiation. The laser intensity at the body surface, although less than the intensity incident at the outer edge of the boundary layer, is greater than initially anticipated due to the strong heating of the boundary layer.

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