A Method for Computing the Nonequilibrium Radiant Emission from Near-Equilibrium Shock Layers

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Introduction

FOR certain planetary entry situations, significant nonequilibrium radiant emission can be obtained when the shock-layer flowfield is near equilibrium. This occurs because the principal nonequilibrium radiators in the flow are species of small concentration, while the species of greatest concentration are near or at equilibrium. Shock-layer radiation and flowfield computations at these conditions, using conventional nonequilibrium bow shock solutions,[1] become impractical because of numerical instabilities and excessive computer times. The present method was developed to overcome some of these difficulties and provide a means of predicting near-equilibrium and radiative shock-layer properties. This is accomplished by using a unique correspondence of blunt-body shock layers[2] to determine streamline locations and pressure fields in nonequilibrium shock layers from a related equilibrium shock-layer solution, making one-dimensional nonequilibrium streamtube computations along selected streamlines through the shock layer, and integrating the results over the volume of the shock layer. This procedure avoids the time consuming, multidimensional computations of the entire flowfield required by nonequilibrium bow shock solutions.

An important application of the present method occurs for Mars entry where the near-equilibrium shock-layer condition exists over a significant portion of many trajectories considered for direct entry into the atmosphere. For the CO_2-N_2 gas mixtures thought to comprise the Martian atmosphere, CN(Violet) is the principal nonequilibrium radiator in the shock layer and is of small concentration, while the species of major concentration are near equilibrium. Results obtained from the present method may be used to satisfy some of the design criteria for atmospheric test probes and have application to the analysis of certain onboard probe experiments such as that described in Ref. 3 for deducing the composition of a planetary atmosphere from shock-layer radiometry.

Description of Method

The present method obtains the chemical and thermodynamic properties of near-equilibrium shock layers by employing one-dimensional, nonequilibrium streamtube computations along a sufficient number of streamlines to adequately represent the shock-layer flowfield. A major part of the method is the procedure for obtaining the boundary conditions (i.e., streamline coordinates and pressure distributions along the streamlines) for the nonequilibrium streamtube computations. This is accomplished by using the blunt-body, shock-layer correspondence described in Ref. 2. This correspondence provides for the determination of streamline locations and pressure fields in nonequilibrium shock layers from related nonrelaxing (i.e., equilibrium or frozen flow) solutions for any real or ideal gas having the same values of freestream velocity, density, and shock shape. The only nonequilibrium quantities required are the shock stand-off distance and stagnation-line pressure distribution. For application to the present method, the correspondence is used to obtain streamline locations and pressures in a nonequilibrium shock-layer from a related equilibrium shock-layer solution (since we are considering the near-equilibrium flow condition).

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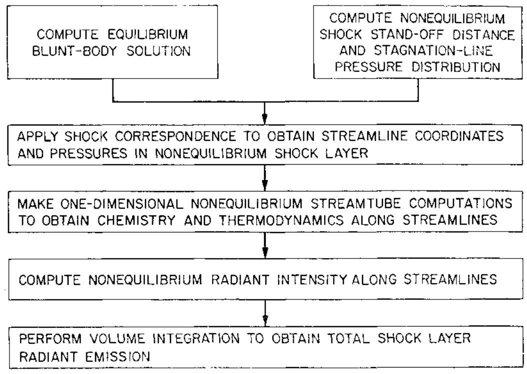


Fig. 1 Flow chart of computational procedure for present method.

The computational procedure for the present method consists, first, of obtaining the equilibrium shock-layer solution for specified freestream conditions using the blunt-body solution of Ref. 4. The nonequilibrium shock stand-off distance and stagnation-line pressure distribution, which are required to apply the shock correspondence of Ref. 2, are obtained using the nonequilibrium bow shock solution of Ref. 1. This computation is made along the stagnation streamline using a simplified system of chemical reactions. The numerically troublesome minor species and chemical processes which contribute little to the shock stand-off distance and stagnation-line pressure distribution are deleted. The nonequilibrium stagnation-line pressure distribution includes the body surface pressures which are approximated using modified Newtonian theory.

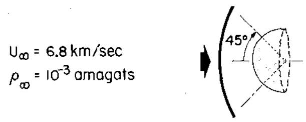
Using the results of the aforementioned computations, the shocklayer correspondence of Ref. 2 is applied to determine streamline locations and pressure distributions along the streamlines in the nonequilibrium shock layer. With these results and the postshock conditions, which are obtained from the bow shock solution of Ref. 1, the complete boundary conditions for one-dimensional streamtube computations are determined. The streamtube computations are made using the nonequilibrium program described in Ref. 5 and provide the chemistry and thermodynamics necessary to determine the radiative properties of the shock layer. The total radiant emission is obtained by including a sufficient number of streamlines to adequately describe the shock-layer flowfield and integrating over the volume of the shock layer, assuming an optically thin gas.

The various steps in the computational procedure for the present method are illustrated by the flow diagram given in Fig. 1. The operations have been combined and computerized to facilitate rapid computations.

Discussion

The application of the present method is demonstrated for some Mars entry conditions where the near-equilibrium shock-layer condition occurs. Results of computations are given for a spherical-faced body flying in a gas mixture consisting of 50% CO_2 and 50% N_2 at a velocity of $U_\infty = 6.8$ km/sec and density range of $\rho_\infty = 10^{-4}$ to 3×10^{-2} amagats (1.225×10^{-7} to 3.675×10^{-5} g/cm^3). The total shock-layer radiant emission I was computed for the first six vibrational levels of the (0,1) band head of CN (Violet), which has been shown to be the principal nonequilibrium radiator at these shock-layer conditions.[6] The chemical model given in Ref. 7 was used, and the computations were carried out to the body sonic point which occurs about 45° from the body centerline.

The accuracy of the present method in predicting the shock-layer radiant emission depends on the number of streamlines used for the computations and is determined by comparisons



METHOD		TOTAL SHOCK-LAYER RADIANT EMISSION FROM CN (VIOLET)	COMPUTATION TIME, minutes
NONEQUILIBRIUM BOW SHOCK		1.00	40
PRESENT	9 STREAMLINES	.89	11.5
	17 STREAMLINES	.94	14.8
	27 STREAMLINES	.98	19.6

Fig. 2 Results of shock-layer radiant emission computations for a spherical-faced body flying in a gas mixture consisting of 50% CO_2 and 50% N_2 at U_∞ = 6.8 km/sec and ρ_∞ = 10^{-3} amagats.

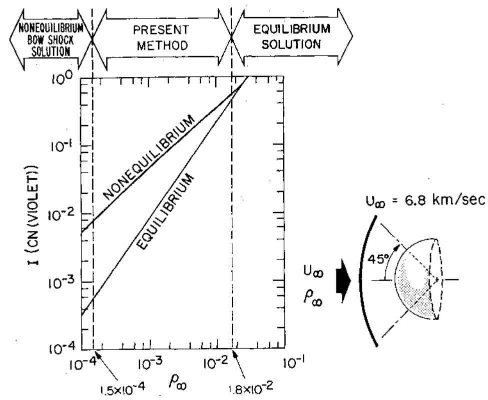


Fig. 3 Total shock-layer radiant emission as a function of freestream density for a gas mixture of 50% CO_2 and 50% N_2 and U_∞ = 6.8 km/sec.

with results obtained from the nonequilibrium bow shock solution of Ref. 1. Results of computations for three groups of streamlines passing through the shock layer are given in Fig. 2 for a freestream density of 10^{-3} amagats (1.225×10^{-6} g/cm^3). These results show that computations using as few as nine streamlines predict the shock-layer radiant emission to within 11% of the bow shock value and require only about 30% of the computing time required for the bow shock solution. As the number of streamlines is increased, results using the present method agree closer to those of the bow shock solution but still require substantially less computing time. Even for the case of 27 streamlines, the present method requires only about one-half the computing time necessary for the bow shock solution but predicts the radiant emission to within 2% of the bow shock value.

The range of freestream densities for which the present method is applicable for the given flight conditions is demonstrated by the results given in Fig. 3. Total shock-layer radiant emission for both nonequilibrium and equilibrium flow are compared in Fig. 3 for a freestream density range of 10^{-4} to 3×10^{-2} amagats. Results of computations show that for freestream densities greater than about 1.5×10^{-4} amagats, the computational time for the present method using 27 streamlines becomes less than that for the bow shock solution of Ref. 1. Hence, the application of the present method for freestream densities greater than 1.5×10^{-4} amagats is advantageous. It is noted that the nonequilibrium radiant emission at this freestream density is about an order of magnitude greater than the equilibrium value. As the freestream density is increased, the difference in computational times between the present method and the bow shock solution of Ref. 1 becomes greater. The results for a freestream density of 10^{-3} amagats have already been discussed and are given in Fig. 2. As the freestream density is further increased, the shock layer approaches equilibrium which occurs at a density of approximately 2×10^{-2} amagats. At a density of about 7.5×10^{-3} amagats, the nonequilibrium and equilibrium shock standoff distances are nearly equal, but the nonequilibrium radiant emission is still about twice the equilibrium value. For this freestream density, the bow shock solution of Ref. 1 obtained only about 35% of the complete shock-layer solution in 60 minutes of computing time; whereas the present method achieved a complete solution in about 18 minutes using nine streamlines. The present method, therefore, provides the only practical means for obtaining solutions in this density range where the nonequilibrium radiant emission is still significantly greater than the equilibrium values.

The range of densities for which the present method is advantageous to use for the given flight conditions is summarized in Fig. 3, and is shown to vary from about 1.5×10^{-4} to 1.8×10^{-2} amagats. For densities less than 1.5×10^{-4} amagats, nonequilibrium bow shock solutions are applicable. For densities greater than about 1.8×10^{-2} amagats, where the nonequilibrium radiant emission is only about 10% greater than the equilibrium value, equilibrium solutions may be used.

The foregoing results have shown that the present method provides adequate predictions of the nonequilibrium radiant emission from shock layers in which the flow is near equilibrium. Also, the method may be the only practical means of obtaining solutions for some near-equilibrium conditions where there is significant nonequilibrium radiant emission.

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