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Nonequilibrium Calculation of High-Temperature Radiating H_2-He Flowfield

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Chemical kinetics of high-temperature hydrogen–helium gas mixture behind a shock wave is numerically investigated by integrating rate equations for species concentration in time. State-to-state transition rates are used to determine quasi-steady-state rate coefficients for atomic hydrogen ionization. The electron concentrations in front of the shock wave are deduced by solving the radiative heat transfer equation of molecular hydrogen. The computed incubation time of avalanche ionization is compared with the experimental data and those appeared in past studies. It is found that the precursor photoionization and the associative ionization of the molecular hydrogen are important to determine the ionization time behind the shock wave. The present chemical kinetic models are found to reproduce the shock tube experimental data of the ionization time reasonably well.

Nomenclature

$A(i,j)$ = probability for the transition from upper state i to lower state j, 1/s
$B(i,j)$ = rate coefficient for radiative transition from lower state i to upper state j, 1/s
B_λ = Planck function at wavelength λ, $\mathrm{W/cm^2 \cdot sr \cdot \mu m}$
c_p = specific heat at constant pressure, J/K
E_{e^-} = electron energy, $\mathrm{J/m^3}$
$E_H(i)$ = energy level of state i of atomic hydrogen, J
h = enthalpy, J/kg
h_{f_s} = formation enthalpy of species s, J
I_{p_λ} = flux of photon at wavelength λ, $\mathrm{1/m^3 \cdot s}$
I_λ = radiative intensity at wavelength λ, $\mathrm{W/cm^2 \cdot sr \cdot \mu m}$
k = Boltzmann constant
k_f = collisional ionization rate coefficient, $\mathrm{m^3/s}$
k_r = collisional three-body recombination rate coefficient, $\mathrm{m^6/s}$
l = directional cosine
m = highest bound state quantum number
m_s = mass of a species s particle, kg
$N_H(i)$ = number density of atomic hydrogen in state i, $\mathrm{1/m^3}$
N_s = number density of species s, $\mathrm{1/m^3}$
P = power absorbed by the Lyman α line, $\mathrm{W/m^3}$
p = static pressure, Pa
R_s = production rate of species s, $\mathrm{1/m^3 \cdot s}$
T = translational temperature of heavy particles, K
T_{e^-} = electron temperature, K
t = time, s
U_s = shock velocity, km/s
u = velocity, m/s
X_s = mole fraction of species s
Y_s = mass fraction of species s
x = x coordinate, m
α = collisional–radiative recombination rate coefficient, $\mathrm{m^3/s}$
$\beta(i)$ = rate coefficient for radiative recombination into state i, 1/s
ε_c = Lyman continuum radiation fraction
ε_L = Lyman α absorption factor
θ_s = ionization energy of spices s, J
κ_λ = absorption coefficients at wavelength λ, 1/cm
λ = wavelength, Å
μ = reduced mass, kg
$\bar{\nu}$ = sum of collision frequency divided by mass of a particle, $\mathrm{1/s \cdot kg}$
$\nu_{e^- s}$ = elastic collision frequency between electrons and the other species s, 1/s
ρ = density, $\mathrm{kg/m^3}$
σ_{p_λ} = photoionization cross section at wave length λ, $\mathrm{m^2}$
σ_λ = absorption cross section at wave length λ, $\mathrm{cm^2}$
∇q_{rad} = divergence of radiative heat flux, $\mathrm{W/m^3}$

Subscripts

E = equilibrium state
e^- = electron
s = species
1 = state in front of a shock wave
2 = state behind a shock wave
$*$ = excited state

I. Introduction

THE Galileo probe entered into Jupiter's atmosphere in 1995. To protect the probe from severe radiative heating during the entry flight, the surface of the Galileo probe was covered with ablative heat shield. The surface recession data were successfully obtained along the Galileo probe's entry flight trajectory [1,2]. The flight data have shown a surprisingly low surface recession in the stagnation region, with unexpectedly larger surface recession along the frustum region.

The flight data obtained in the entry flight of Galileo probe offer a unique opportunity to validate computational fluid dynamics (CFD) codes for predicting the aeroheating environment of the entry flows in future outer planetary missions. Because most of the outer planets in our solar system have an atmosphere similar to Jupiter's, which mainly consists of hydrogen and helium, all CFD codes for such purpose should be able to reproduce the flight data of the Galileo probe's entry flight. The larger surface recession along the frustum region of the probe was successfully explained by the injection-induced turbulence model [3,4]. However, the lower surface recession in the stagnation region has not yet been completely reproduced by CFD.

Park [5] has speculated earlier that the thermochemical nonequilibrium could explain such low heating rate in the stagnation region. Because radiative heating from ionized hydrogen is dominant in the shock layer, the narrower ionization region due to the nonequilibrium effect could lower the heating rate at the stagnation point.

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