

# Fourier and Diffusive Heat Transfer in Hypersonic Nitrogen Flows: State-to-State Approach

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**Diffusive  $q_{wrec}$  and Fourier  $q_F$  components of heat transfer in hypersonic nitrogen flows are discussed. Three models of partially catalytic surfaces differing on the vibrational level(s) pumped by the heterogeneous recombination process are proposed: the ground vibrational state model, the last vibrational state model, and the diffuse vibrational state model. A noncatalytic surface is also considered for comparison. State-to-state gas-phase kinetics are coupled to the state-to-state gas–surface interaction. To investigate the effects of the different surface models and of the gas-phase kinetics, two test cases are considered, taking surface temperature and surface recombination probability as parameters. It is demonstrated that both chemical properties and fluid dynamic properties, such as the surface heat flux, are strongly affected by the state-to-state gas-phase kinetics and the heterogeneous recombination model.**

## Nomenclature

$C_N$	= mass fraction of atomic nitrogen, $\rho_N/\rho$
$C_v^v$	= mass fraction of the $v$ th vibrational level, $\rho_v/\rho$
$c_v^{N_2}, c_v^N$	= specific heats at constant volume
$D_N$	= diffusion coefficient of nitrogen atoms in the mixture, $m^2 \cdot s^{-1}$
$E^D$	= dissociation energy, J
$f$	= stream function
$h_v$	= enthalpy of the $v$ th vibrational level, J
$k$	= thermal conductivity coefficient, $kg \cdot m \cdot K^{-1} \cdot s^{-3}$
$k_B$	= Boltzmann constant, $J \cdot K^{-1}$
$m_N$	= atomic nitrogen mass, kg
$m_v$	= $v$ th vibrational-level mass, kg
$N^*$	= nitrogen adatoms density, $part \cdot m^{-2}$
$n_{N_2}, n_N$	= molecular nitrogen and the atomic nitrogen number densities, $part \cdot m^{-3}$
$Pr$	= Prandtl number
$p$	= pressure, $N \cdot m^{-2}$
$q$	= heat flux, $W \cdot m^{-2}$
$q_F$	= heat flux due to thermal conductivity (Fourier flux), $W \cdot m^{-2}$
$q_{Tjump}$	= heat flux due to temperature jump, $W \cdot m^{-2}$
$q_{wrec}$	= heat flux due to heterogeneous recombination, $W \cdot m^{-2}$
$Sc$	= Schmidt number
$S_T$	= source term of the energy equation
$S_v$	= source terms of the continuity equations
$T$	= temperature, K

$T_e$	= temperature at the boundary-layer edge, K
$T_g$	= gas temperature at the surface, K
$T_w$	= surface temperature, K
$v, w$	= species indices
$v_{N_2}, v_N$	= molecular and atomic nitrogen thermal velocities, $m \cdot s^{-1}$
$\gamma_v$	= surface recombination probabilities
$\epsilon_{rot}$	= rotational energy, J
$\epsilon_{vib}^v$	= vibrational energy, J
$\eta$	= coordinate normal to the surface
$\theta$	= $T/T_e$
$\rho$	= total density, $kg \cdot m^{-3}$
$\rho_N, \rho_{N_2}$	= N, $N_2$ densities, $kg \cdot m^{-3}$
$\rho_v$	= density in the $v$ th vibrational level, $kg \cdot m^{-3}$

## Subscripts

$e$	= external edge of the boundary layer
$w$	= wall

## I. Introduction

CHEMICAL–PHYSICAL models of hypersonic flows have been widely investigated to characterize the complex phenomenology occurring during reentry of vehicles into planetary atmospheres. After the shock, molecules in both vibrationally and electronically excited states and atoms in excited electronic states are formed and diffuse through the boundary layer interacting with the surface. Moreover, atoms recombining on the surface produce vibrationally and electronically excited molecules. Large improvement has been achieved in describing the coupling between vibration and dissociation/recombination processes by using multitemperature and state-to-state approaches [1–3]. Electronically excited states are either ignored or transformed in vibrationally excited molecules [4,5]. As an example, in gas-phase recombination of atomic nitrogen, the formed  $N_2(A^3\Sigma_u^+)$  is transformed in a molecule in the ground-state vibrationally excited level of quantum number  $v = 25$  [5].

The interaction of vibrationally excited molecules with surfaces and the formation of vibrationally excited molecules from the catalytic recombination of atomic species are generally ignored. Both processes are actively investigated nowadays by molecular dynamics (MD). The main results of MD [6–8] can be summarized as follows:

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