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Laminar and turbulent heating predictions for mars entry vehicles

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ABSTRACT

Laminar and turbulent heating rates play an important role in the design of Mars entry vehicles. Two distinct gas models, thermochemical non-equilibrium (real gas) model and perfect gas model with specified effective specific heat ratio, are utilized to investigate the aerothermodynamics of Mars entry vehicle named Mars Science Laboratory (MSL). Menter shear stress transport (SST) turbulent model with compressible correction is implemented to take account of the turbulent effect. The laminar and turbulent heating rates of the two gas models are compared and analyzed in detail. The laminar heating rates predicted by the two gas models are nearly the same at forebody of the vehicle, while the turbulent heating environments predicted by the real gas model are severer than the perfect gas model. The difference of specific heat ratio between the two gas models not only induces the flow structure's discrepancy but also increases the heating rates at afterbody of the vehicle obviously. Simple correlations for turbulent heating augmentation in terms of laminar momentum thickness Reynolds number, which can be employed as engineering level design and analysis tools, are also developed from numerical results. At the time of peak heat flux on the $+3\sigma$ heat load trajectory, the maximum value of momentum thickness Reynolds number at the MSL's forebody is about 500, and the maximum value of turbulent augmentation factor (turbulent heating rates divided by laminar heating rates) is 5 for perfect gas model and 8 for real gas model.

1. Introduction

Currently, Mars has been the most frequently visited planet in the solar system in order to search for extraterrestrial life and do some scientific interest [1]. Since 1960s, more than 42 vehicles have been launched to investigate Mars by National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), the Union of Soviet Socialist Republics (USSR) and Russian Space Agency (RSA), among which at least 14 times attempted to land on the surface [1].

As the vehicle entries the Martian atmosphere with high velocity from the space, the progressions of physical interactions ensue around the vehicle. The flowfield and aerothermal environment of the vehicle become complicated [2]. Firstly, real gas effect, the complicated physical and chemical phenomenon, begins to take into effect when the temperature of the atmosphere around the vehicle is high enough to change the atmosphere's thermal properties and induce chemical reactions on account of the strong compressible effect of the shock wave and the viscous effect [2,3]. Secondly, different from Earth atmosphere, Martian atmosphere consists of nearly 97% carbon dioxide (CO_2) and 3% nitrogen (N_2) by volume [1,2]. Considering carbon dioxide is composed of three atoms, it has three vibration modes at high temperature [4]. Therefore the specific heat ratio of Martian atmosphere is lower than Earth atmosphere at the same high temperature, resulting in a thinner shock layer. Lastly, regarding the high entry velocity, large vehicle's size and complex lifting entry of the future Mars entry vehicles, the laminar boundary layer of the aeroshell transits to turbulence, increasing the heating levels remarkably [1,5,6]. Turbulent heating, a potential source for large uncertainty, will play an important role in the thermal protection system (TPS) design of future Mars entry vehicles [1,5,6]. As a consequence, the complicated flow field and physical interactions will produce the highest heating levels which is important for TPS. Therefore the laminar and turbulent heating of the vehicle need further investigation.

Two distinct methods, thermochemical non-equilibrium gas model (real gas model) [2,7–10] and perfect gas model with specified effective specific heat ratio [9,11], are successfully used to simulate the aerodynamics and aerothermodynamics of Mars entry vehicles when the real gas effect is significant. Real gas model considers the chemical reactions in the flow and non-equilibrium process of internal energy such as transitional energy, rotational energy, vibrational energy and electronic energy [3]. Original real

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Nomenclature

ρ_i	species density
ρ	density
p	pressure
u	X direction velocity component
v	Y direction velocity component
w	Z direction velocity component
E	total energy
E_v	vibrational energy
ω_i	mass rate of production of species i
S_v	vibrational energy source term
J	Jacobian
Ma	Mach number
Re	Reynolds number
T	translational-rotational temperature
T_v	vibrational temperature
k_{tr}	the frozen thermal conductivity for transitional energy
k_v	the frozen thermal conductivity for vibrational energy
h_i, $h_{v,i}$	the total enthalpy and vibrational enthalpy of species i
Y_i	mass fraction of species i
M_i	the molecular weight of species i
$k_{f,r}$	forward rate coefficient of chemical reaction r
$k_{b,r}$	backward rate coefficient of chemical reaction r
$C_{f,r}$	parameter of chemical reaction r
$n_{f,r}$	parameter of chemical reaction r
$E_{f,r}$	parameter of chemical reaction r
T_d	control temperature
γ	specific heat ratio
η	density ratio
k	the turbulent kinetic energy
ω	the rate of dissipation of energy
μ	total viscosity
μ_L	laminar viscosity
μ_T	turbulent viscosity
D_i	total diffusion coefficient of species i
$D_{L,i}$	laminar diffusion coefficient of species i
Cp	specific heat at constant pressure
Pr	laminar Prandtl number
Prt	turbulent Prandtl number
Sc	laminar Schmidt number
Sct	turbulent Schmidt number
ϕ	turbulent augmentation factor
Re θ	laminar momentum thickness Reynolds number

Subscript

i	species
r	chemical reaction

gas model [12] includes species continuity equations, three momentum equations, and three energy equations describing vibrational, electronic, and total energies respectively. Two-temperature model is developed for simplification by assuming that vibrational temperature equals to electronic temperature [12]. Therefore the final real gas model includes two energy equations describing vibrational and total energies. Analogizing the high temperature real gas to perfect gas with a constant specific heat ratio, perfect gas model is simplified to contain one continuity equation, three momentum equations, and one energy equation [9,11]. This model requires an approximation to real gas effect behind the strong shock wave with an appropriate specific heat ratio [9,11]. The two methods discussed above have been used widely to investigate the aerodynamics and aerothermodynamics of Mars entry vehicles [7–11,13–18].

In the current study, real gas model and perfect gas model with specified effective specific heat ratio are utilized to investigate the laminar and turbulent heating of Mars entry vehicle named Mars Science Laboratory (MSL) [6]. The numerical results of the two distinct gas models are compared and analyzed in detail. Simple correlations for turbulent heating augmentation (turbulent heating rates above laminar heating rates) in terms of laminar momentum thickness Reynolds number, which can be employed as engineering level design and analysis tools are also developed from both the model's results.

2. Numerical method

All the test cases are calculated by an in-house code developed by the authors. The main algorithms of the code are presented as follow.

2.1. Governing equations

The non-dimensional steady Navier–Stokes equations written in a body fitted coordinate system are given by [19–21]

$$\frac{\partial \tilde{Q}}{\partial \tau} + \frac{\partial \tilde{F}}{\partial \xi} + \frac{\partial \tilde{G}}{\partial \eta} + \frac{\partial \tilde{H}}{\partial \zeta} = \frac{Ma}{Re}\left(\frac{\partial \tilde{F}_v}{\partial \xi} + \frac{\partial \tilde{G}_v}{\partial \eta} + \frac{\partial \tilde{H}_v}{\partial \zeta}\right) + S \tag{1}$$

For real gas model:

$$\tilde{Q} = 1/J\left(\rho_i, \rho u, \rho v, \rho w, \rho E, \rho E_v\right) \tag{2}$$

$$S = 1/J\left(\omega_i, 0, 0, 0, 0, S_v\right) \tag{3}$$

For perfect gas model with specified effective specific heat ratio:

$$\tilde{Q} = 1/J\left(\rho, \rho u, \rho v, \rho w, \rho E\right) \tag{4}$$

$$S = 1/J\left(0, 0, 0, 0, 0, 0\right) \tag{5}$$

where ρ is density, ρ_i is species density, u, v, w are the velocity components, E is total energy, E_v is vibrational energy, ω_i is mass rate of production of species i, S_v is vibrational energy source term, τ means time, J is the Jacobian of the transformation, $\tilde{F}$, $\tilde{G}$, $\tilde{H}$ are inviscid fluxes, and $\tilde{F}_v$, $\tilde{G}_v$, $\tilde{H}_v$ are viscous fluxes. ξ, η, ζ are the generalized coordinate respectively.

The inviscid fluxes of the real gas model are defined below.

$$\tilde{F} = \frac{1}{J}\begin{pmatrix} \rho_i U \\ \rho u U + p\xi_x \\ \rho v U + p\xi_y \\ \rho w U + p\xi_z \\ (\rho E + p)U \\ \rho E_v U \end{pmatrix}, \tilde{G} = \frac{1}{J}\begin{pmatrix} \rho_i V \\ \rho u V + p\eta_x \\ \rho v V + p\eta_y \\ \rho w V + p\eta_z \\ (\rho E + p)V \\ \rho E_v V \end{pmatrix}, \tilde{H} = \frac{1}{J}\begin{pmatrix} \rho_i W \\ \rho u W + p\zeta_x \\ \rho v W + p\zeta_y \\ \rho w W + p\zeta_z \\ (\rho E + p)W \\ \rho E_v W \end{pmatrix} \tag{6}$$

where p is pressure and calculated by Dalton's law, ξ_x, ξ_y, ξ_z, η_x, η_y, η_z, ζ_x, ζ_y, ζ_z are the metrics. U, V, W are the contravariant velocities and defined as follow.