Hypersonic Flow Analysis Including Finite Rate Ablation Thermochemistry

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Abstract

The design and correct sizing of thermal protection systems of re-entry bodies requires reliable simulation tools that can compute surface recession rate and temperature histories under general heating conditions. A formulation of a finite-rate surface boundary conditions for carbonaceous material ablation with pyrolysis gas injection is developed and implemented in a 3-D reacting Navier-Stokes equation solver, to predict ablation response of carbon and carbon-phenolic heat shields on reentry space vehicles. Validation of the approach is carried out by comparison with literature experimental data. Results show a satisfactory agreement with data and emphasize that including nitridation reaction may yield a significant overprediction of graphite mass blowing rate.

1. Introduction

One of the most challenging aspects of thermal protection system (TPS) design is to predict the desired coupling between the material response and the external flow. The modeling of gas/surface interactions has been the subject of considerable interest, because the coupling that occurs has been shown to have a dramatic effect on the net heating level induced by the gas and on the response of the heat-shield surface. Computational coupling between high-temperature fluid dynamics and material thermal response has taken many forms. A widely used numerical approach for predicting ablation was developed in the late 1960s [1]. The technique uses a boundary layer approach for the fluid dynamics and a one-dimensional in-depth heat conduction and charring response procedure for the material thermal response. With improvements in computational algorithms and advances in computer hardware, Navier-Stokes based approaches have become of standard use for coupling to material thermal response predictions [2, 3, 4, 5]. In most computations, the surface recession rates are determined by solving the surface energy balance with pre-calculated thermochemical ablation tables relating surface temperature and pressure to a dimensionless surface mass flux owing to ablation [6]. These tables are generated assuming that the ablating surface and ambient gas are in chemical equilibrium [7, 8]. This approach has been widely used for many engineering applications.

The present state of the art in fluid-material coupling is represented by loose coupling of a high-fidelity CFD flow solver with a material thermal response code [9]. Neverteless, two major restrictions are still present in these state of the art coupled solutions. The ablation models are currently largely based on the surface equilibrium assumption and the effects and importance of non-equilibrium ablation models are only beginning to be explored [10, 11, 12, 13]. The convective heating and surface recession rate predicted by the chemical equilibrium surface chemistry is usually reasonably conservative and is considered to be sufficient when the nonequilibrium computation is too expensive or unlikely to be achieved. Tables are established by solving the chemical equilibrium relations and the elemental species balance equations with thin-film transfer theory. If the chemical species concentrations, such as a chemical nonequilibrium shock layer with the presence of radiation, must be precisely defined in the flow simulation, then the chemical equilibrium surface conditions are no longer sufficient. Attempts were made to modify tables to include some nonequilibrium effects and to better fit ablation data, but the gas-phase nonequilibrium ablation products cannot be determined without a finite rate simulation. Moreover, the coupling between CFD solver and material response code is currently made considering non-ablating flowfield solutions [9]. This means that the effect on the flowfield solution of the ablation and pyrolysis gas injection and of variable surface temperature are treated only approximately, relying on the use of mass and energy transfer coefficients and semi-empirical relations. The limits and the errors introduced by these approximations are discussed in [14, 15, 16].

The objective of this work is the study of hypersonic re-entry flows coupled with gas-surface interaction phenomena occurring at the interface between TPS-materials and boundary-layer. The main goal is to couple a CFD solver (in-house) with gas-surface interaction modeling to allow surface ablation and surface temperature distributions to be determined as part of a solution that also contains more sophisticated ablation models based on finite-rate surface chemistry. The purpose of this work is to obtain the full Navier-Stokes solutions with finite rate surface ablation conditions for carbon-based materials, using available surface kinetic models, and to perform parametric studies to understand their performance and enable future improvement for the simulation of planetary mission Earth reentries. Carbon-based materials are selected as the heat-shield materials in this study because their interactions with air are better understood. As more is known about the interactions of other heat-shield materials with ambient gases, this same computational methodology can be applied for other ablators. Because the entire flowfield is to be solved, the thin-film theory assumption made in establishing the classical B' equilibrium thermochemical tables is no longer needed, and all of the problems associated with the approximation of transfer coefficient and recovery enthalpy are avoided.

The CFD solver uses a finite-volume approach for three-dimensional compressible flows. A standard finite volume Godunov-type formulation is adopted. It is second order accurate in both space and time and uses multi-block structured meshes. The system of equations is approximated by a cell-centered finite volume scheme. The viscous fluxes are approximated by centered differencing, whereas the convective fluxes are computed by means of the solution of a Riemann problem whose left and right states are reconstructed by an interpolation procedure which uses the minmod limiter. The system of ordinary differential equations is advanced in time by means of an explicit Runge-Kutta integration. In addition, the code has been parallelized using the OpenMP directives and it can run on SMP computers.

The formulation of finite rate ablation surface boundary conditions, including recombination, oxidation, nitridation, and sublimation of carbonaceous materials with pyrolysis gas, is developed and integrated with a 3-D Navier Stokes solver. The kinetic model adopted for gas-surface interactions is based on the works of Park [17, 18, 19].

2. Theoretical model

Modeling of both gas and surface chemical reactions is described in this section. Before going into details it is useful to remind that as long as gas-surface reactions are considered two different classes of TPS materials have to be considered: non-pyrolyzing materials and pyrolyzing materials. In non-pyrolyzing materials (e.g. carbon-carbon, graphite...), mass loss only occurs at the surface (thermochemical and/or mechanical erosion). Pyrolyzing materials (Fig. 1) are



Figure 1: Pyrolyzing materials

composites of fiber or fabric reinforcement in a resin matrix (e.g. carbon-phenolic, silica-phenolic...). When heated, the resin experiences a series of chemical reactions that release gaseous by products (pyrolysis) leaving a layer of char or residue. Then the char itself can recede due to chemical or mechanical action by the boundary layer.

A Navier-Stokes solver with integrated gas/surface interaction models and surface balances is used to simulate high-speed high-temperature flows over ablating materials. The developed tool is a finite-volume solver for threedimensional compressible flows which is able to predict the surface recession, temperature, and the convective heat flux distributions of carbon-based heat shields on reentry vehicles. The code solves the time-dependent conservation equations of mass, momentum, and energy for the chemical nonequilibrium flowfield and adopts a standard finite volume Godunov-type formulation. It is second order accurate in both space and time and uses multi-block structured meshes. The system of equations is approximated by a cell-centered finite volume scheme. The viscous fluxes are approximated by centered differencing, whereas the convective fluxes are computed by means of the solution of a Riemann problem whose left and right states are reconstructed by an interpolation procedure which uses the minmod limiter. The system of ordinary differential equations is advanced in time by means of an explicit Runge-Kutta integration. In addition, the code has been parallelized using the OpenMP directives and it can run on SMP computers. Thermodynamic and transport properties are described by curve fits [20].

2.1 Gas-phase chemical reaction model

There are 13 gas phase chemical species that have been considered in this study to simulate carbon ablation in air. The chemical species are: CO_2 , CO, N_2 , O_2 , NO, C_2 , C_3 , CN, C, N, and O CN, H_2 , and H. Five of the species are for air, and the rest are for ablation products. The total number of reactions is 18, including 9 dissociation reactions and 9 exchange reactions. Dissociation reactions:

$CO_2 + M$	\Leftrightarrow	CO + O + M
CO + M	\Leftrightarrow	C + O + M
$N_2 + M$	\Leftrightarrow	N + N + M
$O_2 + M$	\Leftrightarrow	O + O + M
NO + M	\Leftrightarrow	N + O + M
$C_2 + M$	\Leftrightarrow	C + C + M
$C_3 + M$	\Leftrightarrow	$C_2 + C + M$
CN + M	\Leftrightarrow	C + N + M
$H_2 + M$	\Leftrightarrow	H + H + M

Exchange reactions:

 $\begin{array}{rcl} \mathrm{NO} + \mathrm{O} & \Leftrightarrow & \mathrm{N} + \mathrm{O}_2 \\ \mathrm{N}_2 + \mathrm{O} & \Leftrightarrow & \mathrm{NO} + \mathrm{N} \\ \mathrm{CO} + \mathrm{O} & \Leftrightarrow & \mathrm{O}_2 + \mathrm{C} \\ \mathrm{CO}_2 + \mathrm{O} & \Leftrightarrow & \mathrm{O}_2 + \mathrm{CO} \\ \mathrm{CO} + \mathrm{C} & \Leftrightarrow & \mathrm{C}_2 + \mathrm{O} \\ \mathrm{CO} + \mathrm{N} & \Leftrightarrow & \mathrm{CN} + \mathrm{O} \\ \mathrm{N}_2 + \mathrm{C} & \Leftrightarrow & \mathrm{CN} + \mathrm{N} \\ \mathrm{CN} + \mathrm{O} & \Leftrightarrow & \mathrm{NO} + \mathrm{C} \\ \mathrm{CN} + \mathrm{C} & \Leftrightarrow & \mathrm{C}_2 + \mathrm{N} \end{array}$

The thermodynamic properties for individual species are approximated by seventh-order polynomials of temperature and the transport properties are approximated by fourth-order polynomials [20]. Mixture properties for conductivity and viscosity are derived from Wilke's rule. The diffusion model is based on an effective diffusion coefficient obtained assuming a constant Schmidt number of 0.7. The gas-phase chemical reactions implemented in the CFD code are taken from the work of Olynick et at. [4] for Stardust earth entry simulation and are mainly derived from the work of Park [19, 21].

2.2 Finite-rate ablation model

If it is assumed that no material is being removed in a condensed phase (solid or liquid), then the general conservation laws at the gas-solid interface for a pyrolyzing material can be written as [1, 22]:

Mass:
$$(\rho v)_w = \dot{m}_g + \dot{m}_c = \dot{m}$$
 (1)

Species:
$$-\rho D_{im} \nabla y_i + (\rho v)_w y_{iw} = \dot{m}_c y_{ic} + \dot{m}_g y_{ig} \qquad i = 1, N$$
(2)

Energy:
$$k\nabla T + \sum h_i \rho D_{im} \nabla y_i + \dot{m}_c h_c + \dot{m}_g h_g - \dot{m} h_w + \alpha \dot{q}_r - \sigma \epsilon T_w^4 - \dot{q}_s = 0$$
 (3)

where v_w stands for the radial velocity in the gas phase due to ablation products injection (both the pyrolysis gas and the char-oxidation product species) while $\dot{m}_c y_{i_c}$ is the rate of production of gas-phase species *i* at the surface due to heterogeneous reactions between the boundary layer hot gases and the solid char. The term $y_{i,g}$ represents the chemical composition of the pyrolysis gas which is injected in the boundary layer. Radiation absorption and emission terms are also included. The conduction term \dot{q}_s is represented by a closed expression available assuming steady state ablation:

$$\dot{q}_{s} = \dot{m}_{c}h_{c} + \dot{m}_{g}h_{g} - (\dot{m}_{c} + \dot{m}_{g})h_{v_{i}}$$
(4)

which is a function of char/pyrolysis gas mass flow rate and enthalpy and takes into account the energy absorbed by the matrix decomposition process and the energy consumed in sensible enthalpy changes of the solid and of the pyrolysis gas. The steady-state ablation approximation is a reasonable assumption when high heating rate conditions are encoutered [22]. At this point, substituting Eq. (4) into Eq. (3), the final steady-state surface energy balance becomes:

$$k\nabla T + \sum h_i \rho D_{im} \nabla y_i - \dot{m} (h_w - h_{v_i}) + \alpha \dot{q}_r - \sigma \epsilon T_w^4 = 0$$
⁽⁵⁾

It is interesting to note that Eq. (5), which is in a convenient form for numerical implementation, can be cast into a more appealing form where each term has a more immediate physical significance, obtained substituting the species equation (2) into the energy equation (3):

$$\underbrace{k\nabla T}_{\text{convective}} - \underbrace{\sum \dot{m}_c y_{i_c} h_i + \dot{m}_c h_c}_{\text{chemical}} + \underbrace{\alpha \dot{q}_r - \sigma \epsilon T_w^4}_{\text{radiative}} - \dot{q}_s = 0$$
(6)

distinguishing convective, chemical, radiative, and conduction heat flux, where the chemical heat flux represents the energy absorbed by the heterogeneous surface reactions which consume the charred material.

The rate of production/consumption of the generic gas-phase species *i* participating in heterogeneous reactions with carbon at the surface, $\dot{m}_{i,c}$, appearing in both the species and energy balances, has to be estimated on the basis of the heat-shield material and the atmosphere composition. The non-equilibrium gas/surface interaction model for carbon in air studied in this work is the one developed by Park [23] consisting of two oxidation reactions, one nitridation reaction, and one sublimation reaction:

$$O + C_s \implies CO$$

$$O_2 + 2C_s \implies 2CO$$

$$N + C_s \implies CN$$

$$3C_s \iff C_3$$

The carbon mass blowing rates due to gas-surface reactions are:

$$\begin{split} \dot{m}_{1} &= \rho \, y_{O} \, \hat{v}_{O} \, (\beta_{O}/4) \, (M_{C}/M_{O}) & (O + C_{s} \Rightarrow CO) \\ \dot{m}_{2} &= 2\rho \, y_{O_{2}} \, \hat{v}_{O_{2}} \, (\beta_{O_{2}}/4) \, (M_{C}/M_{O_{2}}) & (O_{2} + 2C_{s} \Rightarrow 2CO) \\ \dot{m}_{3} &= \rho \, y_{N} \, \hat{v}_{N} \, (\beta_{N}/4) \, (M_{C}/M_{N}) & (N + C_{s} \Rightarrow CN) \\ \dot{m}_{4} &= \rho \left(y_{C_{3},eq} - y_{C_{3}} \right) \hat{v}_{C_{3}} \, \beta_{C_{3}}/4 & (3C_{s} \Leftrightarrow C_{3}) \\ \dot{m}_{tot} &= \dot{m}_{1} + \dot{m}_{2} + \dot{m}_{3} + \dot{m}_{4} = \rho_{s} \dot{s} \end{split}$$

Here, $\hat{v}_i = \sqrt{8kT_w/\pi m_i}$ is the mean molecular speed of the ablation-product species. The total surface mass blowing rate \dot{m}_{tot} and the surface recession rate \dot{s} can be computed from the total carbon mass loss and the char density. The term β is the efficiency (or reaction probability in [23]) of each surface reaction. Here, the terms β_i are given as:

$$\beta_{O} = 0.63 \exp(-1160/T_{w})$$

$$\beta_{N} = 0.3 \quad (\text{Ref. [24, 25]})$$

$$\beta_{O_{2}} = 0.5 \quad (\text{Ref. [26]})$$

$$\beta_{C_{3}} = 1.0 \quad (\text{Ref. [18]})$$

The equilibrium C_3 concentration in Eq. (7) is computed from the saturated equilibrium vapor pressure which is expressed as:

$$p_E = p_E = 5.19 \text{ x } 10^{15} \exp(-90845/T_w)$$
 [dyne/cm²]

The source term $\dot{\omega}_i$ are defined as:

$$\dot{\omega}_{CO} = \dot{m}_1 (M_{CO}/M_C) + \dot{m}_2 (M_{CO}/M_C)$$

$$\dot{\omega}_{CN} = \dot{m}_3 (M_{CN}/M_C)$$

$$\dot{\omega}_{C_3} = \dot{m}_4$$

$$\dot{\omega}_N = -\dot{m}_3 (M_N/M_C)$$

$$\dot{\omega}_O = -\dot{m}_1 (M_O/M_C)$$

$$\dot{\omega}_{O_2} = -\dot{m}_2 (M_{O_2}/2M_C)$$

$$\dot{\omega}_i = 0 \text{ for the remaining gaseous species}$$



Figure 2: Pyrolysis gas composition

The pyrolysis gas composition (Fig. 2) injected into the main flow is considered to be in chemical equilibrium at the wall temperature and pressure. In particular, the elemental mass fractions in the pyrolysis gas are considered to be 37.5% C, 46.3% O, and 16.2% H. The equilibrium species concentrations of pyrolysis gas are computed using a chemical equilibrium code at different values of pressure and temperature and are mostly CO, H₂, and H for typical reentry conditions.

3. Results and Analysis

The general finite rate carbon-phenolic ablation model without pyrolysis gas injection ($\dot{m}_g = 0$) can be used to simulate graphite ablation. The analyzed test case is a study of the interaction between a graphite model and an arc-jet stream, conducted in the Interaction Heating Facility (IHF) at the NASA Ames Research Center. Numerical simulations were performed to reproduce the experimental results which have been presented in two works by Chen and Milos [13], and Chen et. al. [27]. According to the data of Ref. [13] and [27], the first series of arc-jet tests were conducted with a stream enthalpy of 27 MJ/kg and a stagnation point cold-wall heat flux of 2100 W/cm². The stagnation pressure is 0.8 atm according to [13]. The length of the heat pulse is 30 sec. The graphite model is a 10° half angle sphere-cone with nose radius of 1.905 cm. The total length of the model is 8.89 cm. Freestream quantities are reported in Ref. [13] and are listed in Table 1. Surface temperature distribution was measured using an infrared camera and pyrometers. The model is a 10° graphite sphere-cone tested at the NASA Ames Center, whose main properties are reported in Table 1. The graphite model has a nose radius of 1.905 cm and a total length of 8.89 cm and has been tested in the Interaction

Table 1: Arc-Jet	test case	definition
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Property	Value	
Cold-wall heat flux	2100 [W/cm ²]	
Velocity	5354 [m/s]	
Density	0.003 [kg/m ³]	
Temperature	1428 [K]	
Mach number	6	
Mass fractions:		
O_2	0.0001	
N_2	0.6169	
NO	0.0046	
Ν	0.1212	
0	0.2572	

Heating Facility (IHF) at the NASA Ames Research Center. Two dimensional axi-symmetric simulations have been

performed to numerically reproduce this test case. The resulting pressure flowfield is shown in Fig. 3. Two-dimensional



Figure 3: Computed pressure flowfield.

axisymmetric simulations have been performed to numerically reproduce this test case. A single-block grid composed of 30×80 grid points in the axial and normal directions, respectively, is adopted. The grid is constructed such to ensure orthogonality at the surface and is adapted to the Mach contours to achieve proper grid alignment to the shock. In the normal direction, meshes are clustered near the body surface such to accurately capture the near wall phenomena. A grid convergence analysis is also performed to ensure that results are grid independent, performing simulations on a coarse 15×40 and a fine 60×160 grid. All the computations presented are at steady-state condition.

To study the thermochemical erosion of the graphite it is useful to analyze the distribution of the ablation species C_3 and CO. To this goal mass fraction contours of ablating species (C_3 and CO) in the nose region are show in Fig. 4. C_3 is mainly produced in the stagnation region. Downstream of the 45° point surface sublimation ends (due to the



Figure 4: Mass fraction contours of ablating species (C₃ and CO) in the nose region

decrease in wall temperature) and the amount of C_3 produced in the stagnation region is being convected downstream. Differently, CO is present at the surface also downstream of the 45° point and in the conical region. Looking to the distribution of species along the stagnation line (Fig. 5), it can be seen that when surface nitridation is activated, N is fully consumed at the surface. The oxidation and sublimation species, CO and C_3 , are only slightly affected by nitridation. Differently, CN, N, and C distributions are significantly affected by the nitridation reaction. Surface temperature is only marginally affected by nitridation: this is because the net energy exchange due to the surface nitridation reaction is small.



Figure 5: Species distribution along the stagnation line and along the wall with and without nitridation



Figure 6: Wall contours of ablating species C₃, CN, and CO

It is also interesting to note that C_3 peaks at the stagnation point, due to the maximum wall temperature which enhance the sublimation process, and then goes to zero in the conical region (Fig. 6). Differently, CN and CO are present all along the wall. Due to the blowing effect of the nitridation reaction (with CN production), the amount of CO at the wall is reduced when the nitridation reaction is considered.



Figure 7: Mass fraction profiles inside the boundary-layer for species C₃ and CO

The mass fraction profiles of C_3 and CO inside the boundary-layer (Fig. 7), shows that upstream of the 45° point, the C_3 profiles show a maximum at the surface, while downstream they show a maximum away from the surface: C_3 produced in the stagnation point region is being convected downstream. The nitridation reaction does not produce significant differences in the C_3 profiles. Differently from C_3 , the CO wall mass fraction is always maximum at the surface tem There is more CO in the boundary-layer when the nitridation reaction is considered.



Figure 8: Mass fraction profiles inside the boundary-layer for species CN and C

The mass fraction profiles of CN and CO inside the boundary-layer (Fig. 8) show that the CN wall mass fraction is always maximum at the surface. Moreover, the produced CN is soon dissociated into C and N as it diffuses in the boundary-layer. Subsequently, the atomic carbon reacts with atomic oxygen producing CO.

The mass fraction profiles of N_2 and O inside the boundary-layer (Fig. 9) show that, through the dissociation of CN and subsequent oxidation of atomic carbon into CO and recombination of atomic nitrogen into N_2 , the nitridation reaction contributes to oxygen depletion in the boundary-layer. In fact, the nitridation reaction and its coupling with the gas-phase chemistry can modify the oxygen content in the boundary-layer thus influencing the oxidation reaction.

To show the strong coupling between gas-surface reactions and gas-phase chemistry, results with full gas-phase chemistry and with reduced gas-phase chemistry are compared. The reduced gas-phase chemistry model only includes



Figure 9: Mass fraction profiles inside the boundary-layer for species N2 and O



Figure 10: Mass blowing rate distributions with and without the nitridation reaction with different gas-phase chemistry models.

the air chemistry, while it neglects the ablation species chemistry. This means that, with the reduced chemistry model, the ablation products are not allowed to react with each other or with the air species, as they are diffusing across the boundary layer. Predicted carbon mass blowing rate distributions with and without the nitridation reaction with different gas-phase chemistry models (full and reduced) are shown in Fig. 10. The results show that, with the full gas-phase chemistry, the nitridation reaction reduces the oxidation mass rate due to oxygen depletion in the boundary-layer. However, if the reduced gas-phase chemistry model is used, the nitridation product CN is not allowed to dissociate in the boundary-layer and the oxygen depletion mechanism is hence inhibited. This produces a significant increase of the total carbon mass blowing rate. Differently, when the nitridation reaction is not considered, the effect of the gas-phase chemistry on the ablation prediction is much smaller. As the use of the nitridation reaction is giving results which are significantly overestimating the experimental data, it will be not included in the following analysis. It is worth noting that the sublimation mass flux becomes negative (carbon re-condensation at the surface) near the sphere-cone juncture.



Figure 11: Effect of graphite emissivity on carbon mass blowing rate and wall temperature distributions



Figure 12: Effect of material type on carbon mass blowing rate and wall temperature distributions

Figure 11 shows the effect of the graphite emissivity (ranging from 0.7 to 0.9) on the carbon mass blowing rate and wall temperature distributions. A change in the material emissivity directly affects the surface energy balance and hence the surface temperature. The material emissivity also affects the mass blowing rate as the wall temperature variation has a significant effect on the sublimation rate while it is only slightly affecting the oxidation mass rate. This is because carbon oxidation is diffusion-limited in this test case (with both atomic and molecular oxygen being completely consumed at the surface due to the high wall temperature level) and hence it is practically insensitive to the wall temperature variation. This sensitivity analysis shows that, as long as the wall temperature is correctly reproduced,

the model is able to predict the mass blowing rate with good accuracy.

Finally, Fig. 12 shows a comparison of the results obtained assuming a different TPS material: carbon-phenolic. In addition to the assumptions made in energy balance of Eq. (5), the pyrolysis gas injection rate, at steady-state, can be expressed by $\dot{m}_g/\dot{m}_c = (\rho_v/\rho_c - 1)$, where ρ_v and ρ_c are the virgin and char material density, respectively. Thus, assuming a PICA-like carbon-phenolic material, the pyrolysis gas injection rate is around 21% of the carbon char mass blowing rate [13]. When a carbon-phenolic material is assumed, due to the blowing effect of the pyrolysis gas injection, both the sublimation and the oxidation mass rates are reduced as well as the surface temperature. It is interesting to see that the sublimation mass rate is more significantly reduced due to the combined effect of the pyrolysis gas blowing effect and the surface temperature reduction. Despite the oxidation and sublimation mass rate reduction, the total mass rate is increasing due to the added pyrolysis mass rate. Therefore, the total mass blowing rate is higher in the case of carbon-phenolic than graphite.

4. Conclusions

The formulation of a finite-rate surface boundary conditions for carbon-based material ablation with pyrolysis gas injection has been developed for a 3-D reacting Navier-Stokes equation solver, to predict ablation response of carbon and carbon-phenolic heat shields on reentry space vehicles. Solutions for an arc-jet test case, using Park's finite rate ablation model and a 18-species gas-phase chemical reaction model, have been obtained and compared with experimental data. With the nitridation reaction, the model overpredicts the graphite mass blowing rate by almost 40% with respect to arc-jet data at the stagnation point and by 30% at 45° from the stagnation point (assuming a graphite emissivity of 0.9). Without the nitridation reaction, the model underpredicts the graphite mass blowing rate by 7% with respect to arc-jet data at the stagnation point and by 15% at 45° from the stagnation point (assuming a graphite emissivity of 0.9). The agreement with the surface temperature is also satisfactory, especially in the spherical part of the body where the heat fluxes are higher and hence the steady-state ablation approximation represents a suitable assumption. Moreover, if the graphite emissivity is varied to obtain a better agreement with the experimental temperature, the agreement with the experimental mass blowing rate is improved. Therefore, when the wall temperature is correctly predicted, the model is able to predict the mass blowing rate with satisfactory accuracy.

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