

PRACTICAL NAVIER-STOKES COMPUTATION OF FLOWFIELDS WITH ABLATION PRODUCTS INJECTION

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ABSTRACT

CFD codes typically treat fluid/solid boundary conditions in a simplified manner such as constant prescribed temperature or heat flux with zero mass transfer. However, thermal protection materials strongly interact with the flow so that simple CFD surface boundary conditions cannot realistically be used for TPS design. In order to obtain a better estimation of the wall heat flux over an ablating surface, a two-dimensional axisymmetric full Navier-Stokes equation solver is used coupled with surface mass balance and an ablation model. The wall composition is computed basing on equilibrium reactions with the solid phase (graphite) and the species are not allowed to react with each other as they diffuse across the boundary layer. The effect of gas injection in the boundary layer is studied focusing the attention on the wall heat flux and its reduction due to the blowing effect. Flat plate tests are presented. Results are compared with the most commonly used blowing rate correction equations.

NOMENCLATURE

| | |
|----------------|---|
| B' | normalized mass blowing rate |
| C_h | Stanton number for heat transfer |
| C_m | Stanton number for mass transfer |
| D | diffusion coefficient |
| h | enthalpy |
| h_r | recovery enthalpy |
| h_0 | total enthalpy |
| j | diffusive mass flux |
| k | thermal conductivity |
| Le | <i>Lewis</i> number |
| \dot{m} | blowing mass rate |
| p | pressure |
| q_{cond} | heat conduction into the solid |
| q_{rad} | radiative flux to the surface |
| T | temperature |
| u | streamwise velocity |
| v | velocity component normal to surface |
| y | mass fraction |
| $\alpha_{k,i}$ | mass fraction of element k in species i |

| | |
|------------|--|
| ϵ | surface emissivity |
| η | outward normal coordinate |
| λ | blowing correction parameter |
| ρ | density |
| σ | Stefan-Boltzmann constant |
| ω | mass flux due to surface chemical reaction |

Subscript

| | |
|-----|--|
| e | outer edge of boundary layer or freestream |
| i | species |
| k | element |
| s | solid |
| w | wall |

Superscript

| | |
|-----|------------------|
| r | surface reaction |
|-----|------------------|

1. INTRODUCTION

Usually CFD codes use simple surface boundary conditions (i.e. zero mass transfer) and cannot be realistically used to predict the aerothermal heating for the design of thermal protection systems (TPS). An appropriate boundary condition should include energy and multispecies mass balances with surface-kinetics or equilibrium models and surface ablation.

Current methods used to predict the aerodynamics and heatings of reentry vehicles focus their attention on some aspects of the problem at the expense of others. Thus aerodynamic methods concentrate on the flowfield, and rely on other methods to provide material-response characteristics such as surface temperature and ablation rates. On the other end, material-response methods concentrate on the physical and chemical processes associated with surface ablation and heat conduction in the interior of the heat shield in order to predict surface temperature, ablation rate, and internal temperatures, using correlation or highly simplified approaches to provide the aerothermodynamic heating acting on the surface of the vehicle. However, in reality all these phenomena are highly coupled.

The heat flux to the ablating surface is usually computed based on the input non-ablating heat transfer coefficients

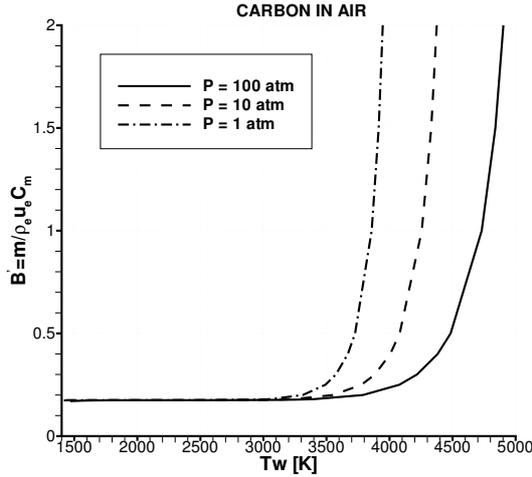


Figure 1. Dimensionless ablation rate for carbon. Full equilibrium surface thermochemistry.

and empirical blowing reduction parameters. The uncertainty in this estimated ablating surface heat flux is high, and consequently the predictions of surface blowing rate and temperature are somewhat inaccurate. Thus, in order to improve the estimation of the heat flux over an ablating surface, a flow solver with ablating surface conditions becomes a requirement. This goal can be achieved by considering that the surface energy and mass balances, coupled with an appropriate ablation model, provide complete thermochemical boundary conditions for a solution of the fully coupled fluid-dynamics/ solid mechanics problem. A significant increase of prediction capability in aerothermal computational fluid dynamics is possible by uniting CFD methodology with surface thermochemistry boundary conditions. However, none of the available Navier-Stokes solvers include complete boundary conditions to realistically determine aerothermal heating and surface ablation rates and a certain amount of decoupling is always performed.

In this study, a general surface boundary condition with mass balance and surface thermochemistry effects is developed for equilibrium gas states adjacent to a non-charring (graphite or carbon-carbon) ablating surface. Based on this formulation, a surface thermochemistry procedure is developed and integrated with a multi-species turbulent Navier-Stokes solver. Radiation and turbulent effects may be important in an ablating flowfield; however, they are not included in this paper.

2. NUMERICAL APPROACH AND SURFACE BOUNDARY CONDITIONS

The analysis of ablative flowfields is performed via a 2-D axisymmetric time-accurate multispecies reacting Reynolds averaged Navier-Stokes solver, ReVMBF (Reacting Viscous Multi-Block and shock-Fitting), based on

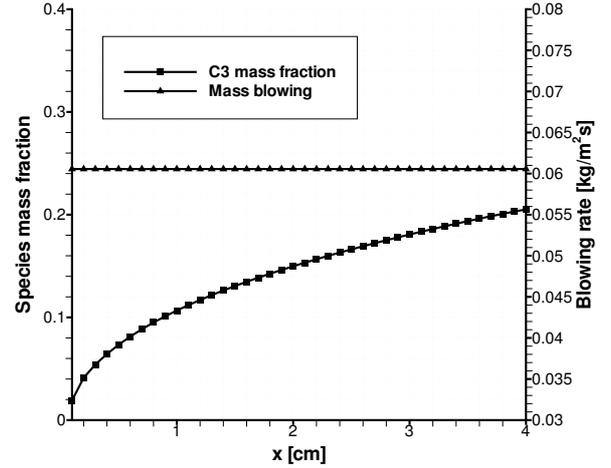


Figure 2. Case 1: Helium. Mass blowing rate (imposed) and C_3 mass fraction at wall.

the approach described by Nasuti & Onofri (1996) and Nasuti (2003). The main features of this method are to discretize the convective terms according to the lambda scheme and to handle shock discontinuities by a fitting technique developed by Moretti (1987). For the present calculations, the thermodynamic and transport properties of the single species are described by the curve fits of Gordon & McBride (1994). Mixture properties for conductivity and viscosity are derived from the Wilke's rule. The diffusion model used is limited to binary diffusion. The binary diffusion coefficients are specified using a constant Lewis number.

The general boundary conditions for a chemically reacting, noncharring ablating surface can be written as:

$$k \frac{\partial T}{\partial \eta} + \sum_i h_i \rho D_i \frac{\partial y_i}{\partial \eta} + q_{rad} = \rho v h_w - \dot{m} h_s + \epsilon \sigma T^4 + q_{cond} \quad (1)$$

which is the surface energy balance (SEB), and:

$$\rho D_i \frac{\partial y_i}{\partial \eta} = \rho v y_i - \dot{m} y_{s,i} + \sum_r \omega_i^r \quad (2)$$

which is the surface mass balance (SMB).

ω_i^r is the mass flux of species i due to surface reaction r , and $y_{s,i}$ is the mass of species i produced in the ablation gas per mass of TPS material ablated. The $y_{s,i}$ are positive for ablation products, negative for atmospheric species which are consumed in the ablation process and sum to unity. For charring (pyrolyzing) TPS materials, additional terms with pyrolysis gas flux have to be considered in the above boundary conditions. Equations 1 and 2 can also be applied on a non-ablating surface, if \dot{m} and ρv are set to zero.

A summation of Equation 2 over all the species yields:¹

$$\rho v = \dot{m} \quad (3)$$

¹the summation made over the diffusive and chemical terms is zero because of mass conservation

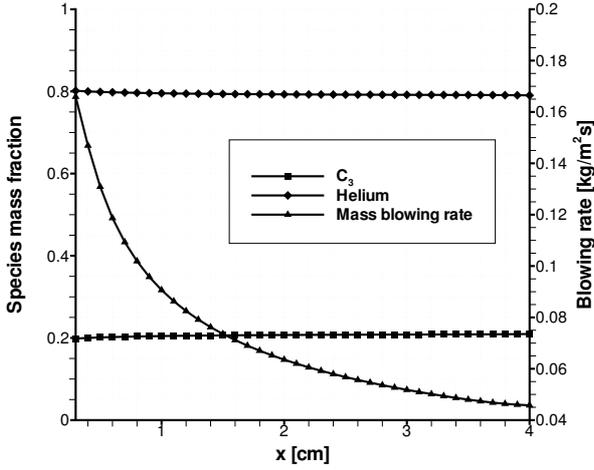


Figure 3. Case 1: Helium. Mass blowing rate and species mass fraction (imposed with equilibrium relations) at wall.

where ρ and v are the density of the gaseous mixture at the wall and the gas-phase convection velocity, respectively.

Making use of Equation 3 and neglecting the radiative and reradiative terms, the surface energy balance Equation 1 becomes:

$$k \frac{\partial T}{\partial \eta} + \sum_i h_i \rho D_i \frac{\partial y_i}{\partial \eta} + \dot{m}(h_s - h_w) = q_{cond} \quad (4)$$

In Equation 4 the terms on the left side account for the heat conduction to the surface, the diffusive chemical energy flux to the surface, and the convective energy flux due to blowing and injection. The term on the right side accounts for heat conduction into the solid. The conduction term q_{cond} is indeterminate from the CFD analyses, unless a numerical or semianalytic CSM (Computational Solid Mechanics) solution is also computed.

If the diffusion coefficients D_i of all species are assumed to be equal, then a summation of the SMB Equation 2 yields a balance equation for each element k , and consequently eliminates the surface reaction term:

$$\rho D \frac{\partial y_k}{\partial \eta} = \dot{m}(y_k - y_{s,k}) \quad (5)$$

where y_k is the elemental mass fraction of the gaseous mixture at the wall and $y_{s,k}$ is the elemental mass fraction of the TPS material.

The use of the elemental mass balance equation (5) instead of the species mass balance equation (2) permits to bypass the entire discussion about governing processes and intermediate steps concerning the number of species, reaction mechanisms, and the associated reaction rates, especially for the complex flowfields with ablation. The advantage of using Equation 5 instead of Equation 2 lies in the fact that the source term due to chemical reactions vanishes in the elemental approach. For what concerns

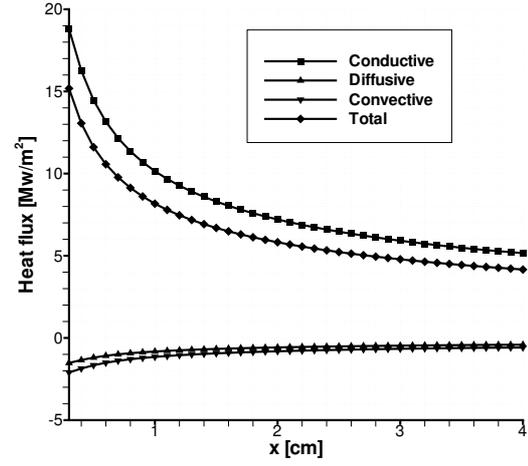


Figure 4. Case 1: Helium. Wall heat fluxes.

the elemental composition of the ablation material (the term $y_{s,k}$) it is easy to determine because it depends only from the material while its species' counterpart composition (the term $y_{s,i}$) depends also from the reaction mechanism with the atmosphere and the atmosphere itself.

3. ABLATION MODEL

In a hypersonic heating environment, noncharring TPS materials, such as carbon-carbon and silica, lose mass only by ablation and melt/fail mechanisms. Detailed modeling of the performance of such TPS materials involves a CSM (Computational Solid Mechanics) and a CFD analysis coupled with surface mass and energy balance (SMB and SEB) and ablation modeling. Coupling the CSM and CFD via the surface energy balance yields the surface temperature. With the surface temperature, the surface mass balance, and a suitable ablation model, CFD analyses yield the wall heat transfer rate (conductive, diffusive and eventually radiating terms).

For TPS materials, the so called thermochemical ablation is the most general and widely applicable ablation model. This model was developed by Kendall et al. (1968) and by Kendall & Rindal (1968). Thermochemical ablation models are obtained from a solution of the equations for thermodynamic equilibrium or nonequilibrium between the TPS material and the atmosphere of interest, coupled with surface mass balance and boundary-layer transfer coefficients. With the boundary layer transfer coefficient approach the diffusional mass flux to the surface can be expressed as:

$$\rho D \frac{\partial y_k}{\partial \eta} = \rho_e u_e C_m (y_{k,e} - y_k) \quad (6)$$

where C_m is a dimensionless mass transfer coefficient and $y_{k,e}$ is the elemental composition at the edge of the

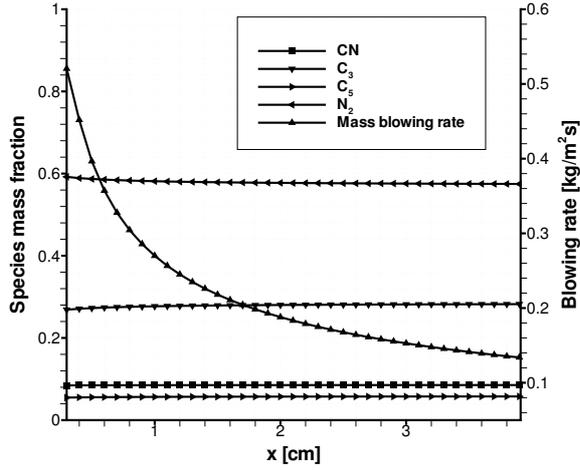


Figure 5. Case 2: Nitrogen. Mass blowing rate and species mass fraction (imposed with equilibrium relations) at wall.

boundary layer. With the use of Equation 6, the surface mass balance Equation 5 becomes:

$$\rho_e u_e C_m (y_{k,e} - y_k) = \dot{m} (y_k - y_{s,k}) \quad (7)$$

Introducing the dimensionless mass flux $B' = \dot{m} / \rho_e u_e C_m$ Equation 7 becomes:

$$y_{k,e} + B' y_{k,s} = (1 + B') y_k \quad (8)$$

which, fixing a value for B' , permits to find the wall elemental composition (edge elemental composition $y_{k,e}$ and material elemental composition $y_{k,s}$ are known):

$$y_k = \frac{y_{k,e} + B' y_{k,s}}{(1 + B')} \quad (9)$$

Once the wall elemental composition is known, assigning the pressure and assuming that the gas is in chemical equilibrium with the wall material (or using kinetic rate-limited reactions between gas species and surface species) the surface temperature can be determined. The net result of the calculations is a set of thermochemical tables relating surface temperature and pressure to a dimensionless surface mass flux owing to ablation. These tables numerically represent a general ablation function $F(T, p, B') = 0$ for a specific TPS material, such as carbon, and a specific boundary layer edge gas, such as air. The shape of the B' curves depends on the material elemental composition, the choice of allowable surface and gas phase species, the atmospheric elemental composition, and whether or not kinetically limited reactions occur.

Figure 1 shows $B'(T, P)$ for pure² thermochemical ablation of carbon in air. As the pressure is increased, a

²no mechanical erosion or spallation

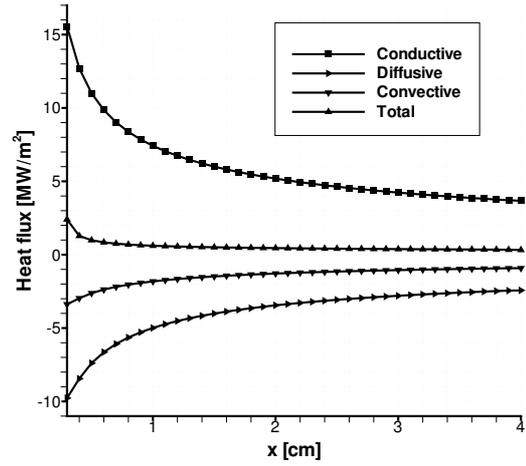


Figure 6. Case 2: Nitrogen. Wall heat fluxes.

higher surface temperature is needed to reach the same dimensionless ablation rate. For any pressures, at the highest ablation rates, carbon sublimation is the primary mass loss mechanism, and C_3 is the predominant ablative species. However, below $B' = 0.2$, surface oxidation reactions dominate, and CO is the major species leaving the surface.

The advantage of using these tables is that, once they have been generated, they are applicable over a wide range of aerothermal heating conditions. The disadvantage is that they are obtained with a very simplified boundary layer approach based on transfer coefficients (represented by the term C_m) to model species diffusion across the BL. In order to obtain the dimensional mass blowing rate we use the following expression, from the definition of B' :

$$\dot{m} = B' \rho_e u_e C_m \quad (10)$$

It is clear that the diffusion coefficient C_m then plays a dominant role in determining the surface ablation rate, and thus the uncertainty in this estimated mass blowing rate can be high. The coefficient C_m is in fact usually obtained via the convective heat transfer coefficient C_h and semi-empirical relations (Spalding, 1963) such as:

$$C_m = C_h Le^{2/3} \quad (11)$$

Sometimes they are even taken as simply being equal (Kuntz et al., 1999).

4. PRESENT APPROACH AND COUPLING TECHNIQUE

The important fact which is explained by the thermochemical ablation model, as shown by Figure 1, is that there is a unique relation between temperature and mass blowing rate. Even modern approaches rely on the use of

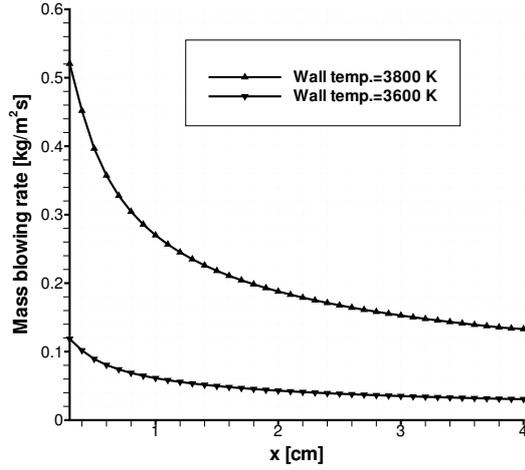


Figure 7. Case 2: Nitrogen. Effect of wall temperature on mass blowing rate.

such tables because of the difficulty of imposing directly the mass balance equation as boundary condition for the CFD code. The design and analysis of a TPS involves transient CSM (Computational Solid Mechanics) analyses of the material and a sequence of steady-state CFD analyses to determine the time-history of the aerothermal heating and coupled mass and energy balance boundary conditions, as reported in the work of Chen et al. (1995) and Olynick et al. (1999). When a coupling with a transient CSM code is not included in the analysis the steady-state ablation is commonly assumed as in the work of Bhutta & Lewis (1992) and Gupta (2000).

In all of these approaches the flowfield boundary conditions at the wall consist of a specified surface ablation rate \dot{m} and a specified wall temperature T_w . When the procedure is coupled with a transient CSM analysis, wall temperature and mass blowing rate come from the material code (which makes use of thermochemical tables); when the procedure is based on the steady-state assumption, the mass blowing rate comes from the energy equation (Equation 1) written in the steady-state form, while temperature can be the sublimation temperature (Gupta, 2000) or is simply assigned to an arbitrary value (Bhutta & Lewis, 1992).

Assigning both temperature and mass blowing rate as boundary conditions can be misleading especially when the steady-state assumption is made; in this case, in fact, the steady-state wall temperature depends on the flowfield and it can be difficult to assign it beforehand (Bhutta & Lewis, 1993). When the wall temperature is specified, and with the wall pressure coming from the flowfield solution, the thermochemical ablation model dictates that there is a unique mass blowing rate coming from mass balance and from thermochemical equilibrium or nonequilibrium reactions between the gas mixture adjacent to the wall and the wall material. Therefore, assuming a fixed wall temperature, the mass blowing rate should be an output instead of an input. When tempera-

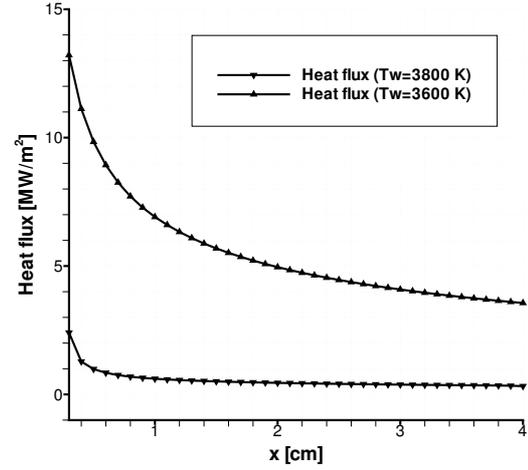


Figure 8. Case 2: Nitrogen. Effect of wall temperature on total wall heat flux.

tures and blowing rates come from a CSM code, the relation between blowing rate and temperature is guaranteed by the use of thermochemical tables. As we have seen, however, these tables rely on a very simplified boundary layer model and the error in the estimation of the mass transfer coefficient C_m to calculate the dimensional mass blowing \dot{m} can compromise the accuracy of the following full Navier-Stokes solution (which has the calculated mass blowing rate as boundary condition).

In this work, efforts have been made in order to bring the process at the base of the thermochemical ablation model inside the CFD code. The advantage of using pre-generated tables is lost but the simplified boundary layer transfer-coefficient approach has been totally removed.

Coupling Technique

Assuming chemical equilibrium between the wall mixture of gases and the solid TPS material, with the pressure coming from the flowfield³ and with the wall temperature assigned, the chemical composition at wall can be obtained using a free energy minimization procedure⁴. From the known wall species composition, the wall elemental composition is easily obtained with the relation:

$$y_k = \sum_i \alpha_{k,i} y_i \quad (12)$$

where $\alpha_{k,i}$ is the mass fraction of element k in species i . Also the diffusive mass flux of element k can be obtained with:

$$j_k = \rho D \frac{\partial y_k}{\partial \eta} = \sum_i \alpha_{k,i} \rho D \frac{\partial y_i}{\partial \eta} \quad (13)$$

³assuming zero pressure derivative in the normal direction: $\frac{\partial p}{\partial \eta} = 0$

⁴elemental composition of the environmental gas and of the wall material are assigned

Finally, with the elemental composition and the elemental diffusive mass flux at wall, the mass blowing rate can be evaluated using Equation 5:

$$\dot{m} = \frac{j_k}{(y_k - y_{s,k})} \quad (14)$$

Among the N_k (number of elements of the system⁵) equations of this type there are $N_k - 1$ relations⁶ so that (obviously) they are not independent and there is only one mass blowing rate. Therefore the mass blowing rate can be obtained from Equation 14 using any of the elements of the system.

During the computational transitory the mass blowing rate boundary condition and the wall chemical composition⁷ are continuously updated until the steady-state condition is reached. Mass blowing rate must be updated continuously because it depends on the boundary layer solution (via the diffusive mass fluxes) and at the same time it affects its development. When steady-state (convergence) is reached, the mass blowing rate is everywhere consistent with the mass balance Equation 2 and the wall composition is in chemical equilibrium with the wall material at the wall pressure and temperature.

5. RESULTS AND DISCUSSION

The procedure described above is applied to a flat plate made up of pure carbon (graphite). Solutions with different environmental gases and boundary conditions are presented in this study to examine their effects on the predictions of flow structure and surface conditions. Chemical reactions between the wall material and the environmental gas are considered to determine the composition of the mixture of gases at wall. Once this composition has been calculated the species are not allowed to further react with each other as they are diffusing across the boundary layer.

Case 1: Helium environment

First, the case with an inert environmental gas made up of pure helium was analyzed. Two kind of wall boundary conditions are investigated. The first with assigned temperature and mass blowing rate and the second with assigned temperature and chemical composition. In the last case the composition at wall is the one in chemical equilibrium with the solid material (graphite) at the temperature and pressure of the wall. Since pressure is varying during the computational transitory, the wall composition is constantly updated. The respect of the elemental mass balance Equation 5 is invoked in both cases. In the first case the mass balance is used to

⁵both material and environmental gas

⁶the elemental composition of the environmental gas is known and fixed as well as the elemental composition of the protection material; the only unknown is their relative amount at the wall

⁷the wall temperature is assigned and fixed but pressure can vary

Table 1. Freestream condition for Test Case 1

| Freestream Conditions | |
|-----------------------|----------|
| pressure: | 1 [bar] |
| temperature: | 4500 [K] |
| Mach number: | 1.8 |
| Composition: | 100% He |

Table 2. Freestream condition for Test Case 2

| Freestream Conditions | |
|-----------------------|------------|
| pressure: | 1 [bar] |
| temperature: | 5000 [K] |
| Mach number: | 3.5 |
| Composition: | 100% N_2 |

compute the elemental composition, while in the second case it is used to compute the corresponding mass blowing rate. The freestream conditions are expressed in table 1. The wall temperature is kept constant and equal to 3500 K. At this temperature and for pressures near 1 bar the primary ablation product is gaseous C_3 (85%)⁸. The equilibrium assumption is acceptable because the wall temperature is sufficiently high (Kendall & Rindal, 1968). Figure 2 shows the C_3 mass fraction at wall along the x direction, with mass blowing rate imposed as boundary condition. As in the work of Bhutta & Lewis (1993), the ablation species (C_3) shows a gradual buildup in the streamwise direction and then asymptote to some value which is less than 1. Figure 3 instead, is obtained imposing the composition at wall to be in chemical equilibrium with the solid material (graphite) at the temperature and pressure of the wall. Wall composition is almost constant because the wall pressure is weakly varying. Mass blowing rate instead, is strongly varying in the streamwise direction according to the growing of the boundary layer. Higher mass blowing rates are experienced near the leading edge of the flat plate where the diffusional mass fluxes are higher. Imposing the wall composition is surely a more adequate boundary condition because it ensures a physical relation between the wall mixture of gases at wall and the solid material. Figure 4 shows the wall heat fluxes computed according to Equation 4. The diffusive and convective heat flux are negative in accordance to the fact that the mechanism of ablation reduces the total wall heat load.

Case 2: Nitrogen environment

⁸for higher temperatures also the production of C_5 becomes important

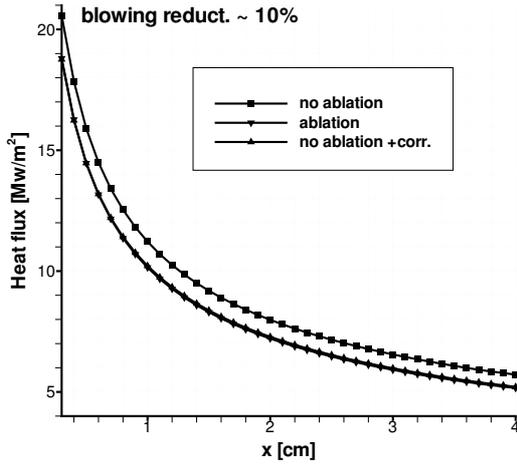


Figure 9. Case 1: Helium. Conductive wall heat flux with and w/o ablation: blowing effect and use of correction equation.

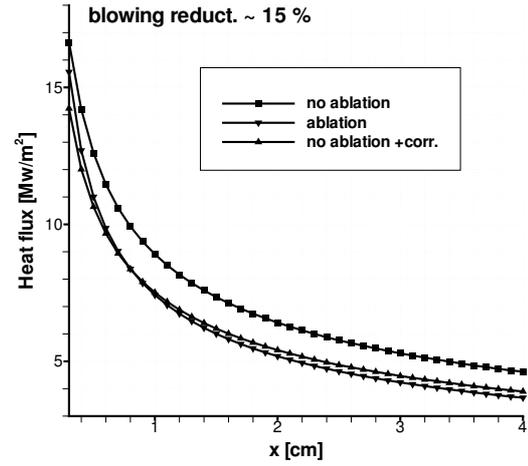


Figure 10. Case 2: Nitrogen. Conductive wall heat flux with and w/o ablation: blowing effect and use of correction equation.

In this case the environmental gas is molecular nitrogen and the ablation products considered are C_3 , C_5 , and CN . With the use of a non-inert environmental gas there are also reactions between the solid material and the gas itself (e.g. nitridation of carbon). The freestream conditions are expressed in table 2. The wall temperature is kept constant and equal to 3800 K . In this case freestream conditions and wall temperature are more severe in order to produce a higher ablation rate. The equilibrium composition between gas phase and solid phase is imposed at wall. The four species considered (C_3 , C_5 , CN , and N_2) make up more than 95% of the equilibrium mixture for the actual condition of pressure and temperature. Species with minor concentrations have been neglected. Figure 5 shows the composition at wall and the mass blowing rate. In this case the blowing rate is more intense because of the higher wall temperature and freestream Mach number. The higher wall temperature increases the ablation products' mass fraction at wall and, together with the higher freestream velocity, increases the species' gradients inside the boundary layer and consequently the diffusional mass fluxes. Figure 6 shows the wall heat fluxes. In this case the heat absorption due to the ablation process is much more evident and the total (conductive + diffusive + convective) heat flux is highly reduced. The same test case has been repeated with the same freestream conditions and a lower wall temperature of 3600 K . Figures 7 and 8 show the effect of a reduction in wall temperature on the mass blowing rate and total heat flux, respectively. A 5% reduction in wall temperature produces an average mass blowing reduction of approx. 75% and an average total heat load increase of approx. 85%. This is because wall temperature is close to the sublimation temperature. Looking at the thermochemical table of Figure 1 it can be seen that, in the knee region of the curve, a slight temperature variation causes a great mass blowing variation.

Comparison with blowing correction equation

In some cases, CSM and CFD codes are loosely coupled, and the thermal response solution is obtained using the nonablating heat flux with assumed blowing reduction parameter. Using a convective transfer coefficient approach the conductive heat flux from the gas to the surface can be expressed as (Chen & Milos, 1999, 2001):

$$q_c = \rho_e u_e C_h (h_r - h_{e,w}) \quad (15)$$

where $h_{e,w}$ is the enthalpy of edge gases evaluated at wall temperature and h_r is the recovery enthalpy which, for the laminar case, is expressed as:

$$h_r = h_0 - \frac{u^2}{2} (1 - \sqrt{Pr}) \quad (16)$$

In Equation 15 the term C_h is the transfer coefficient (*Stanton* number) for heat transfer. A blowing correction allows for the reduction in transfer coefficient due to the transpiration or blowing effect of gases being injected into the boundary layer. The most commonly used blowing rate correction equation is (Chen & Milos, 1999, 2001):

$$C_h = C_{h_0} \frac{2\lambda B_0'}{\exp 2\lambda B_0' - 1} \quad (17)$$

where λ is a blowing reduction parameter, C_h is the heat transfer coefficient for the ablating surface, C_{h_0} is the heat transfer coefficient for the nonablating surface, and B_0' is the dimensionless mass flux evaluated with the nonablating transfer coefficient:

$$B_0' = \dot{m} / \rho_e u_e C_{m_0} \quad (18)$$

With $\lambda = 0.5$ Equation 17 reduces to the classical laminar-flow blowing correction.

Using Equations 15 and 16 to evaluate the unblown Stanton number C_{h_0} , and Equations 18 and 11 to evaluate the dimensionless mass flux B_0' , Equation 17 can be used to compute the corrected heat transfer coefficient. With the corrected heat transfer coefficient the ablative surface heat flux can be evaluated via Equation 15.

Figures 9 and 10 show the computed conductive heat fluxes for Test case 1 and 2 with and without ablation. Results are compared with the corrected nonablating heat flux using the methodology above mentioned. For Test case 1 the conductive heat flux is reduced approximately by 10% and the corrected curve shows a perfect agreement with the computed one. For Test case 2, with a more intense blowing, the reduction is approximately of 15% and the agreement between computed and corrected heat flux is slightly worse. The blowing reduction equation seems to work better in case of lower ablation rates, as one would easily expect.

6. CONCLUSIONS

The general surface boundary conditions with mass balance of chemically equilibrated gas adjacent to an ablating surface were derived. A computer procedure based on these surface conditions was developed and integrated with a two-dimensional axisymmetric full Navier-Stokes equation solver. Solutions with various surface boundary conditions were obtained to study the effects on surface composition and ablation rate. The solutions indicate that, when imposing mass blowing rate as boundary condition, the wall composition is regulated by boundary layer development and has no relations with the solid phase. Imposing the wall composition to be in equilibrium with the material solid phase, instead, allows to find the correct axial distribution of mass blowing rate which satisfies the mass balance equation. Mass blowing rates, wall species compositions, and surface heat fluxes were obtained for two different environmental gases over a flat plate. Results for blowing and nonblowing surfaces were compared with the most commonly used blowing rate correction equation.

7. ACKNOWLEDGEMENTS

Attendance to the workshop was funded through the IPPW4 student scholarship programme.

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