Abstract

A numerical model of a hydrogen arcjet which includes finite rate dissociation and ionization reactions and separate temperatures for electrons and heavy particles is described. It has not been possible to get solutions using the SIMPLE algorithm to converge with acceptably small residuals, however, the results are sufficiently independent of relaxation path to allow some conclusions to be made. The flow in a 30 kW hydrogen arcjet is significantly out of equilibrium. The electron concentration reaches about a third of the equilibrium value in the constrictor and remains above equilibrium in the nozzle. The electron temperature is well above the heavy gas temperature in most of the flow and approaches it at the nozzle exit. The model calculations underpredict the performance seen in experimental data. The procedures for obtaining non-equilibrium transport properties are described. Chemical kinetic rates, species diffusion coefficients, and electron thermal conductivity appear to be of particular importance.

Introduction

If electrically powered arcjets could be designed to have high specific impulse and good thermal efficiency, they could provide a substantial cost reduction for orbital transfer and station keeping missions. Limited understanding of the complex, nonlinear interactions in the ionized propellant has hindered the development of high efficiency arcjet thrusters. The complexity of the heat addition process and strong coupling between the heat addition and the flow make it difficult to predict the effect of design changes and to interpret experimental results.

A computational model developed at UTSI to study laser powered thrusters and radio frequency gas heaters has been adapted to provide a tool to help understand the physical processes in arcjet thrusters. The approach is to include in the model those physical and chemical processes which appear to be important, and then to evaluate our judgment by the comparison of numerical simulations with experimental data. A description of the model and some preliminary calculations of an ammonia arcjet were presented at the 21st International Electric Propulsion Conference (IEPC). 1 A paper presented at the AIAA 27th Joint Propulsion Conference (JPC) 2 describes some of our experiences in modifying the model to use hydrogen as the propellant, particularly with regard to the effect of transport properties on the calculated results. The results of experiments performed at NASA Lewis Research Center 3 were used to challenge the model results in a paper presented at the 22nd IEPC. 4 The comparison of model results with experimental exit plane velocity and temperature data from an argon arcjet was presented at the 28th JPC. 5 The present paper describes changes to the model to include species conservation equations and an electron temperature which differs from the heavy particle temperature. These changes remove the assumption of chemical and local thermodynamic equilibrium. The results are compared with data from reference 3 and with equilibrium calculations.
The Numerical Model

The numerical framework for the model is a Navier-Stokes solver based on the SIMPLE algorithm of Gosman and Pun, modified by Rhie to handle both subsonic and supersonic flows in body fitted coordinates. Jeng included heat addition from a laser induced plasma, and Rhodes, in a study of radio frequency heating, added a magnetic field equation with coupled heat release.

The SIMPLE algorithm used in this work is a solver for equations of the form:

$$\nabla \cdot \tau_{ij} \phi = \nabla \cdot \Gamma_{ij} \nabla \phi + S$$

where $\phi$ represents the axial, radial, and azimuthal velocities $(u, v, w)$, the static enthalpy $(H)$, the mass continuity equation (solved for the pressure $(p)$), the electron temperature $(T_e)$, and the species concentrations $(\alpha_i)$. The transport coefficients $(\Gamma)$ are those appropriate for each variable. Terms which will not fit into either the convective or diffusive form are lumped into a source term. The equations are transformed from body fitted coordinates to a unit grid. The transformation results in mixed derivatives from the diffusion term which are also added to the source term. Finite difference equations are obtained in terms of the variable at each point and its four adjacent neighbors. These equations are solved sequentially with under-relaxation using a tridiagonal matrix solver. Updated values of the dependent variables are used as they become available and old values are used where the updated ones have not yet been calculated. The procedure is repeated until the sums of the residual errors have been reduced to suitably small values. Stability is insured by using upwind differencing for convective terms when the grid Reynolds number is greater than two, and including fourth order pressure smoothing.

Governing Equations

The form of the momentum and continuity equations are unchanged by the relaxation of the equilibrium assumption. However, the solution to these equations will change because the density distribution is not expected to be the same with equilibrium and non-equilibrium flow.

There are several choices for the form of the energy equations used to get the electron and heavy gas temperature. We chose to use the electron energy and the static energy for the mixture of electrons and heavy species since at least formally the energy balance for the mixture is the same for equilibrium and non-equilibrium flows.

Static Mixture Energy

In the mixture energy equation $\phi$ is the static enthalpy per unit mass $(H)$ and the diffusion term is $\nabla \cdot k \nabla T$. The enthalpy of a gas mixture is:

$$H = \sum h_i \alpha_i$$

and

$$\nabla H = \sum [h_i \nabla \alpha_i + \alpha_i \nabla h_i]$$

For equilibrium flow

$$\nabla T = \nabla H/c_{peq}$$

and $\Gamma_H$ is $k/c_{peq}$. For non-equilibrium flow:

$$\nabla T = \nabla H/c_{ph} - \alpha_e c_{pe} \nabla T_e/c_{ph} - \sum h_i \nabla \alpha_i/c_{ph}$$

where subscript $h$ represents the heavy species and subscript $e$ represents electrons. The transport coefficient $(\Gamma_H)$ becomes $k/c_{ph}$ and the resulting terms with $\nabla T_e$ and $\nabla \alpha_i$ are added to the source term.

In equilibrium flow the term describing the energy transport by diffusion of species $(D \sum h_i \nabla \alpha_i)$ can be combined into the thermal conduction since the species gradients may be written as functions of the temperature gradient. This term must be treated separately in non-equilibrium flow and is included in the energy equation source term.

Electron Energy

The assumption of LTE made in our previous work is relaxed in the current model by assuming the electron gas and the heavy particles have separate temperatures both with a Maxwell-Boltzman distribution. This required a
separate energy equation for the electron gas. In this equation the electrical heating is balanced by electron convection, conduction, diffusion, and energy transfer to the heavy particles by collisions. The form of the equation and the included terms are modeled from Park.\textsuperscript{10}

\[
\nabla \cdot \rho u \alpha_e \hbox{\textsubscript{e}} - \nabla \cdot [k_e \nabla T_e + h_e D \nabla \alpha_e] \\
- \rho u \cdot \nabla p_e = S
\]

where

\[
S = q_{ce} + q_{ch} + q_{in} - q_r
\]

This equation differs from the others in that the convection term contains the electron concentration (\(\alpha_e\)). This term may be written:

\[
\nabla \cdot \rho u \alpha_e \hbox{\textsubscript{e}} = c_p e \nabla \cdot c_p e T_e + h_e 0 \nabla \cdot \rho u \alpha_e
\]

since the electron specific heat (\(c_p e\)) and reference enthalpy (\(h_e 0\)) are both constants. The convective electron flux (\(\rho u \alpha_e\)) is used instead of the total flux (\(\rho u\)) which appears in the other conservation equations, and the second term on the right hand side is moved into the source term. This allows us to use the electron temperature (\(T_e\)) as the dependent variable.

The electron thermal conductivity (\(k_e\)) is taken to be the value calculated from the transport property routines. This includes electron/heavy collisions and according to Park\textsuperscript{10} should be reduced by the ratio of frequency of electron/electron collisions to the total number of electron collisions, so that the value used here may be somewhat high. The diffusion coefficient (\(D\)) is the common diffusion coefficient used for all the species described in the section on transport properties.

The term describing the work done by the electron-pressure gradient (\(\rho u \cdot \nabla p_e\)) is obtained using the assumption that the electrons share the bulk velocity with the heavy species. The electron partial pressure is:

\[
p_e = p T_e x_e / [T_h - (T_e - T_h) x_e]
\]

where \(x_e\) is the mole fraction of electrons.

The term \(q_{ce}\) represents the energy transfer between the heavy gas and the electron gas resulting from elastic collisions of electrons with the heavy species,

\[
q_{ce} = \sum 2n_e m_e / m_i \nu_i 3/2k(T - T_e)
\]

The collision frequency (\(\nu_i\)) is evaluated from the temperature dependent collision cross-sections for electron/heavy collisions evaluated at the electron temperature using the formulations found in the transport properties program.

The term \(q_{ch}\) represents the energy transport to the electron gas resulting from the participation of electrons in chemical reactions. With the definition of enthalpy used here, a chemical reaction does not change overall gas enthalpy. However, in a two temperature model the energy of a reaction may be split between the energy of the electron gas and the energy of the heavy particles. The assumption used here is that in reactions where an electron is the third body, the dissociation or ionization energy comes from the electron gas, lowering the electron temperature, and the energy of recombination goes to the electron gas raising the electron temperature.

The energy input to the system from electrical heating (\(J^2 / \sigma\)) and work done by the magnetic field (\(J \cdot u \times b\)) are assumed to be deposited in the electron gas and are combined in the term \(q_{in}\). The radiation from the system (\(q_r\)) is calculated using an empirical equation derived from equilibrium calculations. Previous calculations have shown that, for the conditions in a hydrogen arcjet, radiation has little influence on the energy balance.

Species

Three species equations were added to the system of equations to allow the calculation of flows where dissociation of \(H_2\) and ionization of \(H\) are not in equilibrium. The mixture is assumed to consist of four species: molecular hydrogen (\(H_2\)), atomic hydrogen (\(H\)), ionized hydrogen (\(H^+\)), and electrons (\(e\)). With the assumption of electrical neutrality, the electron and ion concentrations are equal and one species
equation can be eliminated. The equation of conservation of a species may be written as:

\[ \nabla \cdot \rho u \alpha = \nabla \cdot \rho D \nabla \alpha + S_\alpha , \]

where \( S_\alpha \) is the production of the species by chemical reaction. Several methods to solve these equations were tried, and the most successful was to use the same algorithm used for the other equations. This requires an evaluation of the source term \( (S_\alpha) \) prior to using the equation solver. Because of the extreme non-linearity of the chemical rate equations, the expression \( d\alpha/dt \) evaluated using the composition at the start of a time step gives a very poor estimate of the change over a finite time. A residence time is evaluated from the mass in a computational cell divided by flux into the cell, and the species production equations are solved over this time step using a linearized set of equations for the four species. The source term then becomes the change in the species concentration divided by the time for the step.

Chemical rate coefficients with one exception were taken from the work of McCay. This exception is the rate of ionization of \( H \) atom by electrons. This rate was calculated from ionization cross-section data using the procedure described by Keefer. Ionization may occur by a two step process where an electron first excites an \( H \) atom and this atom is then dissociated by a collision with a second electron. This second process will be fast compared to the first because of the relatively small energy required to ionize an excited atom. To implement this effect without introducing a new species (excited \( H \)), the collision cross section was modified to be zero at the excitation potential (10.2 ev) rather than at the ionization potential (13.5 ev). The reaction rate was fitted to an Arrhenius equation with the results shown in Table 1 (reaction no. 5).

### Magnetic Field

The electro-magnetic properties of the fluid are defined by the azimuthal component of the magnetic field \( (B_\theta) \). The radial and axial components of the magnetic field \( (B_r \) and \( B_z \)) are assumed to be zero. The equation describing Ohm's law written in terms of \( B \) is linear in \( B_\theta \) and is solved by direct matrix inversion using a banded matrix solver. The components of the current \( (J_z \) and \( J_r \)), which are used to calculate the heat input, are obtained from numerical derivatives of \( B_\theta \).

### Table 1. Reaction rates for partially dissociated and ionized hydrogen

<table>
<thead>
<tr>
<th>Reaction</th>
<th>( a )</th>
<th>( n )</th>
<th>( E )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) ( H + H + M = H_2 + M )</td>
<td>( 6.40e + 17 )</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2) ( H^+ + e + M = H + M )</td>
<td>( 5.26e + 26 )</td>
<td>2.5</td>
<td>0.0</td>
</tr>
<tr>
<td>3) ( H_2 + e \rightarrow H + H + e )</td>
<td>( 1.91e + 11 - 1.0 )</td>
<td>-203</td>
<td></td>
</tr>
<tr>
<td>4) ( H^+ + e \rightarrow H + h\nu )</td>
<td>( 3.77e + 13 )</td>
<td>0.58</td>
<td>0.0</td>
</tr>
<tr>
<td>5) ( H^+ + e + e \rightarrow H + e )</td>
<td>( 7.08e + 39 )</td>
<td>4.5</td>
<td>-244750</td>
</tr>
<tr>
<td>6) ( H + e \rightarrow H^+ + e + e )</td>
<td>( 1.81e + 14 )</td>
<td>0.0</td>
<td>-244750</td>
</tr>
</tbody>
</table>

Where the forward reaction rate \( k_f = a/T^n \exp(E/RT) \), \( T = T_e \) for reactions 3, 5, and 6, = reversible reaction, > one way reaction, and \( M \) is any third body.
Equation of State for a Two Temperature Neutral Plasma

Starting with the definition of the partial pressure for any species \( p_i = n_i k T_i \), the mixture density \( \rho = \sum n_i m_i \), and the mixture pressure \( p = \sum p_i \), the mixture density may be written:

\[
\rho = \frac{pM}{R}[T_h - (T_e - T_h) x_e] ,
\]

where \( M \) is the mixture molecular weight, \( R \) is the gas constant, and \( x_e \) is the electron mole fraction.

Boundary Conditions

The walls are assumed to be catalytic for electron-ion and \( H \) atom recombination, have a no slip boundary condition, and a specified temperature distribution. As a consequence, the gas is in equilibrium with the enthalpy specified by the temperature with all the velocity components equal to zero on all walls. A zero normal pressure gradient is assumed at all walls. The radial gradients of \( u, h, \) and \( p \) and the values of \( v \) and \( w \) are specified to be zero on the symmetry axis. The axial gradients of all of the dependent variables are constant at the nozzle exit. The pressure level in the flowfield is continuously adjusted to give the desired mass flow in the supersonic part of the nozzle. The inlet velocity is calculated from the mass flow and pressure. The inlet swirl is specified as a constant times the inlet velocity.

The magnetic field is solved in terms of the parameter \( rB_\theta \) which depends only on the current flowing inside the radius \( r \). This parameter is assumed constant on the inlet wall, the cathode, and the anode upstream of the nozzle. It is assumed to decrease linearly to zero along the nozzle wall and to be zero in the nozzle exit plane and on the symmetry axis. This implies that the current from the cathode tip and uniformly enters the anode on the nozzle wall with no current flow to the anode upstream of the nozzle and no current loops outside the nozzle exit. This assumption is based on experimental observations made using a segmented cathode. The model is not capable of describing the details of the current flow from the cathode, so current is assumed to flow axially and uniformly into the gas over an area of about one percent of that of the constriction.

Transport Properties

Transport properties in a two temperature model with non-equilibrium species concentrations depend on the two temperatures and the number densities of all the species. In the equilibrium model, this reduces to functions of temperature and pressure, and table lookup of precalculated properties as a function of two variables is a practical procedure. For non-equilibrium hydrogen, the properties are a function of five variables representing the two temperatures, the total number density, and the degree of dissociation and ionization. Both a five dimensional table lookup and direct calculation at each field point are impractical, so we decided to combine curve fitting, table lookup, and some simplifying assumptions to give a procedure that is both accurate and reasonably fast. One requirement is that the properties vary smoothly over a wide range of variables to avoid instabilities while the solution is converging.

The program we are using to obtain the transport properties uses theoretical and experimental collision cross-section data to obtain collision integrals, and from these the properties are calculated. The original code used tabulated cross-section data with linear interpolation and extrapolation for energy levels not covered by the tables. At temperatures above about 30,000 K, extrapolation could give negative cross-sections. The code was modified to use the data fitted as functions of the log of the cross-sections which can approach zero at high temperatures, but cannot go negative. It was found that the transport properties at constant pressure and species mole fraction could be fitted to an equation of the form \( z = a T^m \) where \( T \) is the electron temperature for electron thermal conductivity \( (k_e) \) and electrical conductivity \( (\sigma) \), and \( T \) is the heavy gas temperature for heavy gas thermal conductivity \( (k_h) \), and viscosity \( (\mu) \). Some cases with high electron concentration and low temperature gave negative results for shielded Coulomb interactions. This problem was avoided by omitting
these cases from the curve fits.

The thermal conductivity of the electron gas used in the electron energy equation is taken to be \( k_e \). Park\(^9\) shows that this value is probably too high since part of the energy transfer implicit in this coefficient is to heavy particles.

For \( k_e \) and \( \sigma \), the coefficients \( a \) and \( n \) are functions of pressure and electron concentration, but were found to be relatively insensitive to the degree of dissociation so the latter factor is not accounted for in the fit coefficients. The coefficients are tabulated in a two dimensional array and are evaluated at the field point by linear interpolation. The properties \( k_h \) and \( \mu \) are calculated for each species and are combined for the mixture. For the electron/ion pair, the fit coefficients were found to be functions of pressure, while for \( H_2 \) and \( H \) they are constants. The best way found to get the mixture properties is to sum the product of the mole fraction and the species property. For these mixtures, this gave results much closer to those calculated for the mixture than using the Wilke mixture rule.\(^17\)

The above procedure was checked by comparing its results with those for equilibrium mixtures using the transport property program. The agreement is within a few percent for all the cases checked.

Energy transport by radiation is modeled as an optically thin component which results in a direct energy loss from the system, and an optically thick component which is used to define an equivalent thermal conductivity using the Rosseland approximation.\(^18\) The Rosseland conductivity is fitted as a function of electron concentration, mixture enthalpy, and pressure for equilibrium hydrogen. This empirical equation is used for the non-equilibrium case, although it has not been checked against calculations for these cases. An effective thermal conductivity for the gas mixture is calculated as the sum of the internal conductivity and the conductivity from the Rosseland approximation. This term is not included in the conductivity of the electron gas.

The binary diffusion coefficients (\( D_{ij} \)) are equal to \( cT^2/p \), where \( c \) is a function of \( p \) for \( D_{H,H_2} \) and a constant for \( D_{H,H^-} \) and \( D_{H_2,H^-} \). The coefficients involving ions are multiplied by \( (1 + Te/Th) \) to account for ambipolar diffusion. In these flows there are few locations where \( H_2 \) and the electron/ion pair coexist. It was decided to use a single diffusion coefficient for the mixture rather than the much more complicated, but correct, method of calculating multicomponent diffusivities. To provide a smooth transition across regions where all three components coexist, a heuristic mixture rule is used.

\[
D = \frac{(\alpha_1\alpha_2 D_{12} + \alpha_1\alpha_3 D_{13} + \alpha_2\alpha_3 D_{23})}{(\alpha_1\alpha_2 + \alpha_1\alpha_3 + \alpha_2\alpha_3)}
\]

This gives the correct answer for a mixture of any two components and provides a smooth transition where three component mixtures exist.

**Discussion of Calculated Results**

One of the cases from a high power arcjet test series\(^3\) is used to demonstrate the results of the model calculations. The same computational grid (Fig. 1) was used for all the calculations on this case. It must be stated from the outset that the numerical algorithm we are using does not converge well for this problem. These are extremely non-linear equations, and the solutions

Figure 1. Arcjet grid
converge to a point and then oscillate. We have tried a number of techniques to get a well converged solution, including using very low relaxation parameters, and alternating between calculations where the temperatures and species are held constant, and calculations where the pressure and velocities are held constant. None of the approaches we have tried have worked very well. However, the best results, based on global conservation, have been obtained by iterating all the variables to get the minimum residuals, and then freezing the temperatures and species concentrations, and iterating the velocities and pressure to minimize their errors. Even though the details of the solution cannot be trusted to give the correct answers, there are several factors which make it worthwhile to present these results. First, two computer calculations with different relaxation factors were made where overall mass continuity in the nozzle and energy conservation at the exit plane were within a few percent. The solutions at the exit plane were nearly the same for both these calculations. The non-equilibrium solutions are different enough from the equilibrium solution of the same problem to show the importance of including finite rate processes. In addition, the solutions can be used to show the relative importance of the physical processes which are being modeled.

Exit plane profiles of temperature, total enthalpy, velocity, and species concentration (Figs. 2 through 5) demonstrate the consistency of the solutions of the non-equilibrium model when the number of iterations and relaxation factors were varied while attempting to get converged solutions. The exit plane temperature predicted by the kinetic model decreases almost linearly with radius, while the equilibrium model predicts a profile with a broad peak near the centerline with a centerline temperature nearly twice as high. The exit plane total enthalpy and velocity profiles are typical of those expected where radial transport is significant. They all have roughly the same shape with significantly higher centerline values for the equilibrium case. As a result of the higher temperature on the centerline, the equilibrium model predicts more ionization on the centerline than the kinetic model.

Figure 2. Comparison of equilibrium and finite rate exit plane temperature

Figure 3. Comparison of equilibrium and finite rate exit plane total enthalpy

Figure 4. Comparison of equilibrium and finite rate exit plane velocities
However, the electron concentration falls rapidly as the temperature falls, while in the kinetic prediction it only decreases slightly with radius and then falls rapidly near the wall.

Neither the equilibrium nor the kinetic model predict the performance well. A comparison of these calculations with data (Table 2) show the kinetic model underpredicts the ISP and efficiency by about twice as much as the equilibrium model overpredicts it. It is possible that this is a result of poor convergence or inadequate modeling of the processes. However, we feel that it is equally likely that inaccurate chemical rates or transport properties are the cause. All of the performance improvement predicted by the equilibrium model occurs between 40 and 80 percent of the nozzle radius (Fig. 6). This is the region where the temperature predicted by the equilibrium model drops and the corresponding velocity is still substantially higher than that predicted by the finite rate model. The shape of the profiles in this region depend strongly on the amount of mixing and on the chemical composition, which, in turn, are dependent on the transport properties and chemical kinetic rates.

The amount that the finite rate calculations are out of equilibrium may be shown by comparing the predicted species concentrations with those in equilibrium at the predicted temperature. At the nozzle exit plane both the $H_2$ and electron concentrations are several orders of magnitude above their equilibrium values on the centerline (Fig. 7). The $H_2$ concentration increases with radius and approaches the equilibrium value at about two thirds of the distance from the centerline to the wall. The electron concentration is above the equilibrium value over the entire exit plane. A similar comparison on the nozzle centerline (Fig. 8) shows that the reaction kinetics reduce the peak ionization to about a third of the equilibrium value at the predicted heavy gas temperature, reduce the rate of recombination as the gas cools, and essentially freezes the electron concentration during the expansion in the nozzle.

![Figure 5. Comparison of equilibrium and finite rate exit plane species concentration](image1)

![Figure 6. Radial distribution of specific thrust](image2)

Table 2. Calculated and experimental arcjet performance

<table>
<thead>
<tr>
<th></th>
<th>Kinetic</th>
<th>Equilibrium</th>
<th>Data $^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current $-A$</td>
<td>221.6</td>
<td>221.6</td>
<td>221.6</td>
</tr>
<tr>
<td>Power $-W$</td>
<td>29320.</td>
<td>29320.</td>
<td>29320.</td>
</tr>
<tr>
<td>Mass $-mg$</td>
<td>91.5</td>
<td>91.7</td>
<td>91.5</td>
</tr>
<tr>
<td>Thrust $-N$</td>
<td>1.05 - 1.10</td>
<td>1.33</td>
<td>1.25*</td>
</tr>
<tr>
<td>Isp $-sec$</td>
<td>1171 - 1223</td>
<td>1485.</td>
<td>1387.</td>
</tr>
<tr>
<td>eff $-kW$</td>
<td>6030 - 6571</td>
<td>9712.</td>
<td>8495.*</td>
</tr>
</tbody>
</table>

$^*$calculated from Isp
The kinetic model also predicts a significant difference between the electron temperature and the heavy gas temperature throughout most of the flowfield. On the centerline, both temperatures rise abruptly at the cathode and then fall as the plasma mixes with the surrounding gas (Fig. 9). The peak temperatures are not reliable since the gradients are large compared to the grid spacing in this region and an approximate model is used for the current leaving the cathode. The temperatures level off in the constrictor with the electron temperature about twice the heavy gas temperature, and then decrease again during the nozzle expansion, becoming nearly equal at the nozzle exit. At the nozzle exit (Fig. 10), the electron and heavy gas temperatures are essentially equal, except near the wall where the electron temperature rises sharply. This is a region where the power dissipated goes into a relatively small number of electrons which are very strongly heated. Similar temperature profiles are seen about a third of the way from the end of the constrictor to the nozzle exit (Fig. 11), except that the two temperatures are out of equilibrium at the centerline, and relax toward equilibrium at a point near the wall. The accuracy of the electron temperature depends strongly on the accuracy of the transport property models since the electron thermal conductivity and electrical conductivity depend on electron concentration and tempera-
For the finite rate case, the factor required to correct the input power is about .7, indicating the predicted conductivities are too low. The most significant collisional process turns out to involve the energy transferred to the electron gas when the electrons are the collision partner in an ionization or dissociation reaction. This provides a strong coupling between the electron temperature and the rates of these reactions. Electron thermal conduction is very significant where the electron temperature gradients are high so that the thermal conductivity of the electron gas must be predicted accurately if accurate values of the electron temperature are to be predicted.

The concentration of a species in a computational cell depends on a balance between production by chemical reactions, net diffusion into the cell, and convection through the cell. The ratio of diffusion to convection in the electron conservation equation was calculated for all the cells downstream of the cathode. In over half the cells, diffusion is greater than conduction, and in almost 20 percent, it is over 100 times greater (Fig. 13).
Conclusions

It does not appear likely that well converged solutions to the non-equilibrium arcjet flowfield can be obtained with the modified SIMPLE algorithm. There is too much explicit dependence of one variable on another as well as the implicit dependence through the transport properties to expect a procedure which solves for one variable at a time to be satisfactory. In spite of this, solutions have been obtained which, to a large degree, are independent of the solution path, and some conclusions may be drawn about the effect of including chemical and thermodynamic equilibrium in the arcjet model. The gas in a hydrogen arcjet appears to depart significantly from equilibrium. The maximum electron concentration is about 15 percent compared to the complete ionization seen in the equilibrium model. The electron temperature is much higher than the heavy gas temperature over much of the flow, particularly near the centerline and near the anode surface.

Because of the high temperature and small size, the flow in an arcjet is very dissipative, making accurate transport properties essential if predictive answers are required. The electrical conductivity, electron thermal conductivity, and the rate of $H_2$ dissociation and $H$ ionization all have a non-linear dependence on electron temperature, and, in turn, are controlling terms in the electron energy equation. In addition to making this equation difficult to solve, the converged solution is dependent on the models used for these terms. Diffusion has been shown to be a dominant term in the species conservation equations over much of the flow, and more consideration should be given to how this term is modeled. Energy tied up in ionization or dissociation is not available to produce thrust, and, thus, will reduce performance. However, the distribution of this energy at the nozzle exit, which depends on radial transport in the nozzle, is equally important. An accurate calculation of performance requires that the mixing and composition changes in the nozzle be calculated correctly, which cannot be done without accurate transport properties and kinetic rates.

Acknowledgement

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References


