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ARCJET SPACE THRUSTERS

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INTRODUCTION

Electrically powered arcjets which produce thrust at high specific impulse could provide a substantial cost reduction for orbital transfer and station keeping missions. There is currently a limited understanding of the complex, nonlinear interactions in the plasma propellant which has hindered the development of high efficiency arcjet thrusters by making 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 judgement by the comparison of numerical simulations with experimental data.

The results of this study have been presented at four technical conferences. These papers are included as an appendix to this report. Two additional papers are in preparation for presentation at the 22nd International Electric Propulsion Conference (IEPC). A description of the model and some preliminary calculations of an ammonia arcjet were presented at the 21st 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]. One of the papers for the 22nd IEPC describes the changes to the model to include non-equilibrium species conservation equations and an electron temperature which differs from the heavy particle temperature [6].

The other describes the results of using the equilibrium model to evaluate the effect of wall temperature on the performance of a hydrogen arcjet [7].

The details of the work accomplished in this project are covered in the individual papers included in the appendix and will not be repeated. In the following sections we present a brief description of the model covering its most important features followed by a summary of the effort, for the most part in chronological order.

NUMERICAL MODEL

The numerical framework for the model is a Navier-Stokes solver based on the SIMPLE algorithm of Gosman and Pun [8], modified by Rhie [9] to handle both subsonic and supersonic flows in body fitted coordinates. Jeng [10] included heat addition from a laser induced plasma, and Rhodes, in a study of radio frequency heating [11], added a magnetic field equation with coupled heat release. This algorithm is used is used to solve of the conservation equations for the axial, radial, and azimuthal velocities, the static enthalpy, and the mass continuity equation (solved for the pressure), and for the non-equilibrium flow model, the electron temperature and the species concentrations. This procedure for solving the governing equations was chosen because of its availability and because of our previous experience with it. The results of this choice have been mixed. For the equilibrium model in cases with hot walls converged solutions with small residual errors have been obtained, although a large number of iterations are required. Any additional complication to the calculation has made convergence more difficult and in some cases particularly those with cold walls and with the non-equilibrium flow calculations the smallest residual errors obtainable are larger than we would desire.

MODELING ASSUMPTIONS

The flow in this arcjet model is assumed to be laminar, viscous, axisymmetric and time steady. The azimuthal magnetic field is the only significant component of the B-field. The wall and gas inlet temperatures are specified, as are the mass flow, total current and power.

A number of additional assumptions are built into the model. Some of these are included because of the complexity of relaxing them before the results show the necessity of doing so, and some reflect our approach to solving the problem. The most obvious example of the first type is the assumption of chemical and thermodynamic equilibrium which is used in most of this work and has been relaxed only because calculations with equilibrium flow do not appear to satisfactorily describe the spatial distribution of transport properties and cannot account for recombination losses in the nozzle. Another significant assumption is that we can specify the axial current distribution into the anode. All the calculations made to date have assumed a linear distribution of current based on measurements made with a segmented anode [12]. This assumption combined with a specification of the total current defines the azimuthal component of the magnetic field on the walls of the arcjet. To calculate the wall current distribution would require a more accurate calculation of the electrical conductivity than we believe is possible with the current state of the art in transport property calculations as well as make more complicated boundary conditions for the B field calculations. We also specify both current and power input and correct the local heat input to force the total heat input to be correct. This approach also reflects our uncertainty in the correctness of the calculated electrical conductivity.

TRANSPORT PROPERTIES

One of the most critical aspects of the calculation of arcjet performance is the quality of the transport properties. Three different propellant gases have been considered in this work; ammonia (treated as a 3:1 H_2/N_2 mixture), hydrogen, and argon.

The composition of each system was calculated as a function of temperature, and transport properties were then calculated at these temperatures using procedures similar to those described by Devoto [13] which start with collision cross section data for the individual species. For the equilibrium calculations viscosity and thermal and electrical conductivity are tabulated as functions of pressure and temperature and are accessed by the arcjet program by table lookup and interpolation. Energy transported by radiation is estimated using a Rosseland equivalent thermal conductivity [14]. This term and the energy transported by diffusion of species are added to the thermal conductivity. When diffusion is included in the thermal conductivity for argon the predicted exit plane centerline temperature drops 30 per cent.

The evaluation of transport properties for hydrogen in the non-equilibrium program use a different approach. The properties are a dependent on the composition and temperature which in this case are independent variables. Table lookup and calculation from first principals are both impractical, the former because of the number of independent variables and the latter because of the computer time involved. Semi-empirical equations were developed by fitting the results of first principal calculations, and the local transport properties in the code are evaluated from these equations.

Electrical conductivity presents special problems because of its very rapid change with electron concentration at low ionization levels. To avoid ill-conditioning the B-field solution matrix the minimum conductivity needs to be limited to about one mho per meter. For the equilibrium calculations conductivities in the nozzle are linearly extrapolated to the wall value when the temperature is below 10000 K to heuristically account for the excess electrons which the model fails to predict. This has not proved necessary in the non-equilibrium model. Some smoothing of the conductivity values is necessary to prevent excessive gradients which appear to cause solution instabilities. A measure of the accuracy of the calculated electrical conductivity can be obtained from the multiplier used to correct the local power input so that the correct total power is obtained. Typical results indicate the levels may vary from the actual values by as much as a factor of two. Cathode to anode voltage drops calculated from the predicted current and conductivity when compared with experimental values give the same level of uncertainty.

Because of their small size and high operating temperature, transport through diffusional processes is quite important even in the supersonic nozzle of an arcjet. Calculations show that the velocity near the centerline decreases due to viscous effects, even in the presence of a strong favorable pressure gradient. Numerical experiments have shown that even modest differences in transport properties can have significant effect on the calculated arcjet performance. Accurate transport properties for ionized gases are very difficult to obtain, and the uncertainty in transport properties may well be the limiting factor in our ability to accurately calculate the flow and electrical properties in these devices.

NON-EQUILIBRIUM MODELING

The current non-equilibrium arcjet model is only applicable for hydrogen. This limitation exists because the transport routines are specific for hydrogen and do not currently exist for other propellants. These routines use a mixture of curve fits and table lookup to provide a method which is both accurate and fast. This model attempts to account for finite rate dissociation and recombination reactions which result in a departure from chemical equilibrium and uses a two temperature model to describe thermodynamic non-equilibrium. To treat chemical non-equilibrium in the hydrogen system three species equations must be solved. Each of these has terms which describe the convection, diffusion, and production of the individual species. Diffusion has proved to be very important. Because of the large gradients in the flow, in many locations the species equation essentially becomes a balance between production and diffusion. To treat thermodynamic non-equilibrium an energy equation for the electron gas was added to the system of equations. This equation is a balance between convection, conduction, the energy input from electrical heating, and those terms which describe the transfer of energy from the electron gas to the heavy particles. These include both elastic collisions and the inelastic collisions which occur when an electron acts as a third body in a dissociation/recombination reaction. These equations require the evaluation of additional coefficients for the collisional processes. These include chemical reaction rates, elastic collision cross-sections, and electron/electron conduction.

As mentioned earlier, the solutions from this model do not have residual errors as small as would be desired. These errors reach a minimum and then oscillate near this value. This appears to be an instability in the algorithm rather than errors in the code, but you can never be sure until you fix the problem which we, so far, have been unable to do. In spite of this problem, the solutions have value in that they show the relative importance of the physical processes described by the equations and what effect they have on the performance of an arcjet. The results of this study are being documented and will be presented at the International Electric Propulsion Conference in September 1993 [6].

SUMMARY

The arcjet modeling effort began with the development of an equilibrium code for ammonia using the Avco arcjet configuration run by Rocket Research [15] and JPL [16]. This effort was successful, producing a numerical model which converged well and predicted an ISP about 10 per cent higher than the experimental value [1]. At this time H_2 appeared to be a more interesting propellant and the H_2 thermodynamic and transport property data were developed for the model. The revisions were checked by comparing the hydrogen calculations with those for ammonia in the same configuration [2]. Preliminary studies were made which determined that there is a large effect of the transport properties on the calculated performance. It was also determined that ionized hydrogen which is not in chemical equilibrium has transport properties which differ markedly from the equilibrium gas at the same temperature.

Calculations using the UTSI equilibrium arcjet model were then compared with the experimental performance of three hydrogen arcjet configurations over a range of hydrogen mass flow rates and electrical power input [4]. The calculated trends of the variation of specific impulse with specific power and mass flow rate, the variation of efficiency with specific power, and the relative performance for the three nozzle configurations agree with the data. The level of the predicted ISP's are from 0 to 8 per cent higher than the data and the predicted efficiencies are from 0 to 25 per cent higher.

Calculations using the UTSI arcjet model were compared with the measured exit plane velocity and temperature of a small water cooled argon arcjet [5]. The equilibrium thermodynamic and transport properties of the argon atom and the first four ions were calculated and tabulated as a function of temperature for pressures from .01 to 5 atmospheres for use in the model. The model severely under predicts the energy loss from the arcjet used in the experiment. This results in high calculated temperatures and velocities at the nozzle exit. Nozzle constrictor geometry has a significant effect on the predicted centerline temperature at the exit plane.

Equilibrium calculations of a water cooled and a radiation cooled hydrogen arcjet [7] were compared with experimental data [17,18]. The computer code so far has failed to give satisfactorily converged solutions for a arcjet using 300 K hydrogen and water cooled walls. In both the hot and cold wall cases the wall losses appear to be underpredicted.

The development of a model which removes the restriction of assuming chemical and thermodynamic equilibrium has appeared to be necessary since the early phases of this project. The low electrical conductivity near the wall predicted by the equilibrium model requires a heuristic fix which is difficult to justify. The demonstrated sensitivity of the calculated results to transport properties and the sensitivity of the transport properties to the composition combine to make the equilibrium flow results questionable. The computer code has been modified to include non-equilibrium processes and has been tested against experimental data from a 30 KW hydrogen arcjet [6]. The residual errors in the solution are larger than desired, but we believe the code is useful for examining the effect of parameter variations even though the accuracy of the calculated performance is still in doubt.

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