NUMERICAL AND EXPERIMENTAL STUDIES OF HYDROGEN AND NITROGEN FLOWS IN A RESISTOJET

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Abstract
Detailed numerical and experimental studies are presented of flows representative of a hydrazine resistojet. The flows consist of mixtures of molecular nitrogen and hydrogen. Computational results are obtained with the direct simulation Monte Carlo (DSMC) method. Experimental data are presented for two different techniques applied in two different facilities. Measurements of axial velocity and translational temperature are obtained with the coherent anti-Raman scattering (CARS) technique. Data are taken along the axis and in the exit plane of the resistojet nozzle. Comparison of the numerical and experimental results give good agreement indicating that the DSMC technique is suitable for use in improving the design of resistojets. In addition, the method may be employed to estimate plume impingement effects for these thrusters. Performance measurements of thrust are also compared. Compared to this data, the DSMC predictions consistently overpredict specific impulse by 10%. Further study is required to understand this anomaly.

Introduction
Resistojets represent the simplest form of electric propulsion and offer significant improvements over chemical propulsion in terms of specific impulse. These devices have been flown on a number of spacecraft and are replacing chemical rockets on both commercial and military satellites. Despite the confidence in their use, there is a requirement for detailed studies of resistojets for improvement in propulsion performance and to address the issue of spacecraft integration. Design of these devices has been performed based on empirical experience. However, numerical methods are under development that offer the possibility to perform optimization studies on the computer. However, detailed validation studies of the numerical approach is still required. This is the principle goal of the present investigation. Detailed experimental measurements are conducted of basic flow field properties for comparison with computational results. These comparisons are useful in assessing the accuracy of the simulations in describing spacecraft interaction phenomena. Experimental measurements of thrust are also conducted and compared to the simulations. The comparisons are useful in assessing the usefulness of the code for designing thruster configurations with improved propulsion performance.

In the following, details are provided of the resistojet and the flow conditions investigated. The numerical approach is then described. The experimental measurements are obtained using two different techniques in two different facilities. These are all described. Results are then presented in which simulation is compared with measurement.

Conditions Investigated
Flow is considered in a small resistojet designed at NASA Lewis Research Center. A picture of the device is shown in Fig. 1. The nozzle has a throat diameter of 0.66 mm and an exit diameter of 7.06 mm. The nozzle half-angle is 20°. In the experimental investigations, three different nozzles are employed:
one at NASA Lewis Research Center, and two at the Aerospace Corporation. The actual dimensions of each thruster are slightly different and the various geometries are employed directly in the DSMC simulations. In this paper, attention will be focused on results obtained for a mixture of molecular hydrogen and nitrogen. Such mixtures are of particular interest due to the common use of hydrazine as propellant. Flows are investigated for two different stagnation temperatures corresponding to operation with and without the heater turned on. The relevant operating conditions are listed in Table 1. The pressure in the test chamber is designated as $p_3$. While attention is mainly focused on gas mixtures in this paper, specific impulse data for pure hydrogen conditions are also presented. Note that the flow conditions of the gas mixtures studied at NASA Lewis Research Center and at the Aerospace Corporation are slightly different. Numerical simulations are performed to match the flow conditions of each individual experiment. In all cases, the chamber pumping capacity is sufficiently great to preclude any adverse effects on the experimental data. Further information on the thruster is provided in [1] which reported on an investigation of pure hydrogen flow in this device.

### Table 1. Resistojet operating conditions.

<table>
<thead>
<tr>
<th>Test Facility</th>
<th>$\text{H}_2: \text{N}_2$ (mg/s)</th>
<th>$T_e$ (K)</th>
<th>$p_3$ (Pa)</th>
</tr>
</thead>
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<td>294</td>
<td>17-30</td>
</tr>
<tr>
<td>Aerospace</td>
<td>3.32:82.9</td>
<td>660</td>
<td>14-30</td>
</tr>
<tr>
<td>NASA</td>
<td>7.55:0.0</td>
<td>294</td>
<td>0.04-27</td>
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<td>NASA</td>
<td>7.55:0.0</td>
<td>660</td>
<td>0.04-27</td>
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<td>NASA</td>
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<td>294</td>
<td>29-33</td>
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<td>660</td>
<td>30-33</td>
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<td>NASA</td>
<td>7.55:103.6</td>
<td>294</td>
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</tr>
<tr>
<td>NASA</td>
<td>7.55:103.6</td>
<td>660</td>
<td>30-40</td>
</tr>
</tbody>
</table>

### Numerical Code

A computer program based on the direct simulation Monte Carlo method (DSMC) [2] for application to electric propulsion is under development at Cornell University. The DSMC technique models gas flow at the molecular level using particles that are stored in the computer. The motion of particles is decoupled from collisions over a time step that is shorter than the mean time between collisions. The particles move through physical space according to their velocity components. Collisions are computed statistically using concepts from kinetic theory. A computational grid is employed to group together particles that are most likely to collide and to output flow field data. The DSMC code used in this study [3] is implemented efficiently on a Cray C90 computer and has been verified directly against experimental data for flows in small thrusters of nitrogen, helium, and hydrogen [4-6]. Recently, the code was successfully compared to measurements of axial velocity and translational temperature obtained using the CARS technique for flows of pure hydrogen in a small resistojet [1]. The current study extends these investigations to mixtures of hydrogen and nitrogen in the same thruster, and to comparison with measurements of thrust.

The DSMC simulations begin at a location just downstream of the nozzle throat. Flow conditions are specified using isentropic theory, the stagnation temperature, and the mass flow rate. A profile of temperature along the nozzle wall is estimated for the heated cases based on a previous study of a nitrogen resistojet [4].

In simulating the mixture of hydrogen and nitrogen, the modeling of rotational relaxation required particular attention. The rate of rotational relaxation for hydrogen is at least one order of magnitude slower than for molecular nitrogen. Separate relaxation models are employed that have been previously developed and verified for nitrogen [7] and hydrogen [6].

The DSMC calculations proceed from the inlet plane out beyond the nozzle exit plane into the near field plume expansion. This allows direct comparison with some of the experimental measurements that are taken a short distance into the plume downstream of the nozzle exit. The expansion process is assumed to occur into the finite chamber pressure measured experimentally.

The simulations employ up to 40,000 cells and a total of 500,000 particles. Total execution time on a Cray C90 supercomputer is quite long due to the relatively high density. The Knudsen number at the throat of the nozzle in the unheated case tested at NASA Lewis Research Center is about $5 \times 10^{-4}$. While the Knudsen number increases by two orders of magnitude as the gas expands to the nozzle exit, most of the flow remains in the continuum flow regime. In this case, the total time required to obtain the DSMC solution is about 7 hours.

### Experimental Investigations

Two different sets of experimental measurements are reported. Detailed diagnosis of the flow field is obtained using the CARS technique at a facility operated by the Aerospace Corporation. Integrated diagnosis of thrust is obtained at a facility operated by NASA Lewis Research Center. These techniques and facilities are described briefly in the following section.

### Aerospace Facility

At the Aerospace Corporation, measurements of
the flow properties in the interior of the nozzle are made using a nozzle with a series of conical holes cut in its wall to permit optical access to axial points 0.96, 3.84, and 7.20 mm from the throat (positions 1-3 in Fig. 1). An axial exterior measurement (position 4 in Fig. 1) a distance of 11.10 mm from the throat is also made using this nozzle. A second nozzle, nominally identical to the first but without the conical holes, is used for measurement of axial velocity at a series of exterior off-axis points (positions 5-7 in Fig. 1) as well as the exterior axial point 4. The redundant measurement at point 4 is used to observe the effect of the conical holes on the velocity. Measurements are made at plenum gas temperatures of 294 and 660 K. The resistojet is placed in a 1.1 m long by 0.75 m diameter stainless steel chamber which is evacuated with two root pumps in parallel. The jet is mounted on a motorized $x\ y$ stage that permits the motion of the jet along the flow axis and in the vertical plane. The $x\ y$ assembly is placed on another motorized stage that permits rotation of the jet around the measurement point (focal point of the laser beams) in the horizontal plane. This rotation is used for the two orientations required for the velocity measurements. The flow and laser beams are confined to the horizontal plane. All motion is computer controlled from outside the evacuated chamber. Table 1 presents the flow rates, plenum temperature, and test chamber pressure for the measurements. Additional details on this experimental configuration and the accuracy of these measurements are presented in Ref. 1.

**CARS Diagnostic**

A detailed discussion of the CARS technique applied to the resistojet was presented previously [8]. Briefly, CARS is a four-wave mixing process in which a pump beam (at a fixed wavelength) and a Stokes beam (at a variable wavelength longer than the pump wavelength) interact through the third order susceptibility of a medium to create a new beam (at a wavelength shorter than the pump wavelength). When the difference frequency between the two input beams equals a resonance in the medium (in this case in the Q(1) resonance of molecular hydrogen), the strength of the anti-Stokes signal becomes large. In this implementation of CARS, all beams are collinearly aligned, and good spatial resolution is attained by tightly focusing the two input beams. The spatial resolution is measured to be approximately 350 μm along the laser beams and better than 35 μm transverse to them.

The second harmonic output of a commercially available single longitudinal mode (SLM) Nd:YAG laser provides the pump radiation for the CARS process as well as the excitation radiation for the dye laser system. The scanning SLM dye laser produces the tunable narrow-band Stokes radiation required to scan across the Q(1) H$_2$ Raman transition. The performance of the dye laser largely defines the accuracy with which the velocity and temperature measurements can be made.

The axial velocity is inferred from the Doppler shift in the resonance frequency caused by the flow velocity. For collinear beams, the Doppler shift of the anti-Stokes frequency, $\Delta \nu_D$, for a flow velocity, $v$, is simply

$$\Delta \nu_D = \nu_R v \cos \alpha$$

where $\nu_R$ is the Raman shift (cm$^{-1}$), and $\alpha$ is the angle between the laser propagation direction and velocity vector of the flow. For the hydrogen Q(1) line, $\nu_R=4155$ cm$^{-1}$. The frequency shift is obtained from two measurements of the Q(1) resonance. The first is a scan taken within a geometry that will produce no Doppler shift (beams perpendicular to the velocity vector of the flow). The second is a scan taken with the resistojet rotated so the beams have a component along the velocity vector of the flow. For a 30° rotation angle, $v$ (km/s) = 4.81 $\Delta \nu_D$ (GHz). Nonlinearities in the scanning mechanism of the Stokes laser limits the precision of the velocity measurements to about 0.2 km/s which is a relative precision of ±6% and ±10% when the resistojet is operated at 660 K and room temperature respectively.

The measured width of the Q(1) line is used to infer the translational temperature of the hydrogen. For monochromatic waves, the CARS resonance linewidth may be approximated as 1.23 times the Raman Doppler width for forward scattering, i.e.

$$\Gamma = 2.46 \frac{\omega_R}{c} \sqrt{\frac{2kT \ln 2}{m}}$$

where $\Gamma$ is the full width half height (FWHH), $\omega_R$ is the frequency of the Raman resonance, $T$ is the absolute temperature, and $m$ is the molecular mass. This approximation is good below 10 torr for hydrogen. For the Q(1) transition of H$_2$, $\Gamma=77.65 \sqrt{T}$ MHz. Due to broadening effects caused by laser radiation, this simple Doppler relation must be modified. These instrument dependent broadening effects were measured and the results were used to correct the Doppler expression. Details of this correction procedure are presented in Ref. 8. Translational temperatures are more difficult to recover from the data than the velocities due to these intensity dependent corrections. These corrections and the scan linearity of the dye laser limit the precision of the temperature measurements to approximately 30%.
NASA Facility

At NASA Lewis Research Center, steady-state performance testing is conducted with a resistojet having nominally the same dimensions as the devices tested at the Aerospace Corporation. The testing is performed in a 1.5 m diameter by 5 m long stainless steel vacuum facility. The pumping system for the chamber includes four 0.7 m diameter oil diffusion pumps. The oil diffusion pumps are backed with a 0.7 m³/s capacity rotary blower followed by two 0.14 m³/s capacity roughing pumps. Several background pressures are tested in order to cover the range of experimental conditions in other tests [1]. Background pressure is raised by either operating without oil diffusion pumps or adding a nitrogen purge to the tank during resistojet operation. The background pressure during thruster operation ranges from 0.3 to 307 mtorr. The displacement-type thrust stand, described in more detail in the next section, is mounted in a 0.9 m diameter by 0.9 m long test port located on one end of the facility. The test port is isolated from the main chamber with a 0.9 m gate valve for faster vent and purge times.

Performance Measurements

Operational parameters monitored during steady-state performance tests are thrust, hydrogen and nitrogen mass flow rates, stagnation pressure, stagnation temperature, facility pressure, heater current, heater voltage, and nozzle wall temperatures at two different locations. Thrust is measured using a displacement-type thrust stand described by Haag and Curran [9]. The thruster is mounted on a fixture which is free to move axially. A linear variable differential transformer measures the position of the mobile fixture relative to a stationary point. Thrust is determined by relating the relative displacement of the thruster during operation to a displacement caused by a calibration force. Thrust stand calibration is conducted in-situ with a series of 39.2 mN weights which are incrementally added and removed from the thruster fixture. The spring constant for the thrust stand is calculated by dividing the known calibration force by the resultant displacement. Thrust calibration is performed before each test run and the thrust zero is recorded after each data point.

Both hydrogen and nitrogen mass flow rates are measured with thermal-conductivity type mass flow controllers. The units maintain propellant flow rates, accurate to within 1%, by providing a feedback signal to actuate integral solenoid-operated control valves. The mass flow controllers are calibrated in-situ using a constant-volumetric calibration technique. In this procedure, gas would flow through the flow controller into a cylinder of known volume for a given time. Initial and final pressures and temperatures are recorded. Through an assumption of ideal gas behavior, the change in the number of moles within the cylinder is calculated and converted to a mass flow rate.

The remaining parameters are measured with standard laboratory instrumentation which will be described briefly. The stagnation pressure is measured in the resistojet plenum using a strain gage-type pressure transducer. Stagnation temperature on the thruster axis in the plenum is measured with a type-K thermocouple. The thermocouple is electrically and thermally isolated from a radiation half-shield. Facility pressure is measured by a capacitance manometer. Heater current and heater voltage are measured using a Hall-effect current probe and rms voltmeter, respectively. The nozzle wall temperature profile is characterized by two type-K thermocouples mounted at axial distances of 3 and 8 mm downstream of the nozzle throat on the external surface of the nozzle.

The experimental procedure is briefly described as follows. The heater input power is adjusted such that a stagnation temperature of 700 K is obtained. As discussed in Ref. 1, due to inadequate shielding of the thermocouple against radiative heating, it is believed that the stagnation temperature in the NASA Lewis experiments was about 660 K. This is the value assumed in the simulations. The thruster is typically operated for 45 minutes to reach steady-state condition at each operation point. All reported performance data are corrected for thermal shift of the thrust zero which is determined by turning off both power and flow. After the propellant line is evacuated, the new thrust zero is recorded and used in performance calculations. Thrust calibrations are conducted in-situ both before and after test runs to verify calibration slope repeatability.

Results

General features of the nozzle and near field plume expansion region are shown in Fig. 2. This shows the DSMC solution for translational temperature in the heated case investigated at the Aerospace Corporation. The boundary layer formed along the nozzle wall is relatively thin indicating near-continuum flow conditions in the nozzle.

In the following, separate discussion is provided on comparisons of DSMC results and experimental data for: (1) flow field measurements of axial velocity; (2) flow field measurements of translational temperature; and (3) performance measurements of specific impulse.
Axial Velocity

Comparison of the DSMC simulations and CARS measurements for the axial velocity of hydrogen along the nozzle axis for the two stagnation temperatures are shown in Figs. 3 and 4. For the fourth measurement location there are in each case two data points. The filled circle is obtained using the ported nozzle and the open circle is obtained using the solid nozzle. In both cases, the agreement between the two is well within the experimental uncertainty. The DSMC results offer very good agreement with the experimental data for both flow conditions. In the previous study that made comparison between DSMC and CARS for pure hydrogen flows [1], it was found that DSMC appeared to over predict velocity for the heated flows. This is not the case here where the level of agreement is about the same for both heated and unheated cases.

Simulation and measurement of hydrogen axial velocity near the nozzle exit plane are compared for the unheated and heated flows in Figs. 5 and 6. The data are plotted as a function of the angle subtended between the axis and a line drawn from the data location to the point at the nozzle throat on the axis. Very good agreement is again obtained between DSMC and CARS. The decrease in velocity at large angle indicates the presence of a viscous boundary layer formed along the nozzle wall. It is significant that the extent of this boundary layer is well predicted. Most of the fluid that expands into the backflow region behind the thruster originates in the boundary layer. Since every effort is made in spacecraft design to point the thruster away from spacecraft surfaces, it is in the backflow region that much of the interaction effects occur.

Translational Temperature

Reduction of the CARS measurements to translational temperatures is performed only for the flow along the axis. Comparison of the DSMC predictions with the CARS data for the translational temperature of hydrogen at the two stagnation temperatures are shown in Figs. 7 and 8. In both cases the agreement between the two is satisfactory.

An interesting aspect of low-density flows are non-equilibrium effects such as thermal nonequilibrium and velocity slip between different species and different energy modes. These phenomena are simulated directly by the DSMC technique. The degree of thermal nonequilibrium in these flows may be assessed from Fig. 9 which compares the rotational and translational temperatures along the axis for the heated flow. Note that separate rotational temperatures are shown for hydrogen and nitrogen. It is found that the bulk translational temperature is very close to being in equilibrium with the rotational mode of nitrogen. However, due to its significantly slower relaxation rate, the rotational mode of hydrogen is partially frozen at a higher value.

In all of the flows investigated, no velocity slip is found between hydrogen and nitrogen. This is due to the relatively high density conditions employed in the present studies.

Specific Impulse

Comparison of measured and calculated specific impulse is shown in Table 2. As the flow rates are always matched in the experiments and simulations, the specific impulse is determined by thrust. Computed data are included for the test conditions performed at the Aerospace Corporation although no thrust measurements are available. In each case, the specific impulse predicted by the DSMC technique is 10% higher than that measured at NASA. Uncertainties such as modeling of the nozzle wall temperature profile or the stagnation temperature achieved in the heated cases are irrelevant as this difference is consistently observed in both heated and unheated cases. A series of DSMC simulations were performed in which more cells were added, more particles were employed, the gas-surface interaction model was changed, and the gas collision model was changed. Of these, only the collision model made any discernible difference. Using a hard sphere interaction model gave a 2% decrease in specific impulse whereas using a Maxwellian interaction model gave a 3% increase in specific impulse. At this point, the most likely explanation for the 10% discrepancy in the results is a difference in nozzle geometry caused by machining inaccuracies. It is the intention to repeat the thrust measurements at NASA using the unported nozzle tested at the Aerospace Corporation.

Comparison of specific impulse predicted by the DSMC technique for the two facilities in both unheated and heated flows reveals a 10% increase for the conditions investigated at NASA. The total flow rate investigated at NASA is only 30% higher than the Aerospace condition. However, one would not normally expect such a significant rise in Isp for this modest increase in flow rate. The explanation lies in the relative concentration of hydrogen employed in the two different facilities. The flow rate of hydrogen employed at NASA is more than double that employed at Aerospace. The small mass of hydrogen allows this gas to accelerate to larger terminal velocities than pure nitrogen. In the nozzle expansion process, collisions between hydrogen and nitrogen partially accelerate the nitrogen molecules beyond their usual terminal velocities. This increased acceleration of the flow leads to the higher thrust. An increase in
specific impulse of 10% is significant in terms of extending the lifetime of a spacecraft. The present results suggest that seeding a hydrazine resistojet flow with a light gas such as helium or hydrogen could be used to augment the performance of existing propulsion systems.

Table 2. Resistojet thrust data.

<table>
<thead>
<tr>
<th>Test Facility</th>
<th>H₂:N₂ (mg/s)</th>
<th>T₀ (K)</th>
<th>Measured Isp (s)</th>
<th>DSMC Isp (s)</th>
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<tr>
<td>NASA</td>
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<td>660</td>
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Summary and Concluding Remarks

Detailed experimental data have been obtained with the CARS technique for axial velocity and translational temperature of hydrogen in a gas mixture representative of flow in a hydrazine resistojet. These data were used to successfully validate the ability of the direct simulation Monte Carlo method to simulate these flows. The good agreement obtained with the detailed flow field measurements indicates that the DSMC technique may be used with confidence to provide an accurate description of the expansion plume. Hence, the DSMC method is capable of providing an accurate estimate of plume impingement effects such as heating, torques, and contamination.

Comparison of numerical results with experimental measurement of thrust was less satisfactory. The DSMC technique consistently overpredicted specific impulse by 10% for all cases considered. A series of numerical investigations only served to increase confidence in the DSMC results. Further measurements of thrust are required to explain this discrepancy.

A significant increase in specific impulse was found theoretically for a relatively small increase in the amount of hydrogen used in the gas mixture. This offers the possibility of increasing the performance of existing resistojet systems through addition of a gas of small molecular mass. Further studies are required to assess the practical implementation of this idea.

Acknowledgments

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References


Figure 1: Resistojet tested at Aerospace that included holes for optical access to the nozzle flow.

Figure 2: Contours of translational temperature for the heated case investigated at Aerospace.

Figure 3: Comparison of axial velocity along the axis for $T_o=295$ K.

Figure 4: Comparison of axial velocity along the axis for $T_o=660$ K.

Figure 5: Comparison of axial velocity in the nozzle exit plane for $T_o=295$ K.

Figure 6: Comparison of axial velocity in the nozzle exit plane for $T_o=660$ K.
Figure 7: Comparison of translational temperature along the axis for $T_0=295$ K.

Figure 8: Comparison of translational temperature along the axis for $T_0=660$ K.

Figure 9: Computed temperatures along the axis for $T_0=660$ K.