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MODELING OF MICRO THRUSTERS FOR GRAVITY PROBE B

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INTRODUCTION

The concept of testing Einstein's general theory of relativity by means of orbiting gyroscopes was first proposed in 1959 simultaneously by Pugh[1] and Shiff[2], which lead to the development of the Gravity Probe B experiment. Einstein's theory concerns the predictions of the relativistic precession of a gyroscope in orbit around earth. According to his theory, there will be two precessions due to the warping of space-time by the earth's gravitational field. The geodetic precession in the plane of the orbit, and the frame-dragging effect, in the direction of earth rotation. For a polar orbit, these components are orthogonal.

In order to simplify the measurement of the precessions, Gravity Probe B will be placed in a circular polar orbit at 650 km, for which the predicted precessions will be 6.6 arcsec/year (geodetic) and 42 milliarcsec/year (frame-dragging). As the gyroscope precesses, the orientation of its spin-axis will be measured with respect to the line-of-sight to Rigel, a star whose proper motion is known to be within the required accuracy. The line-of-sight to Rigel will be established using a telescope, and the orientation of the gyroscope spin axis will be measured using very sensitive SQUID (Superconducting Quantum Interference Device) magnetometers. The four gyroscopes will be coated with niobium. Below 2K, the niobium becomes superconducting and a dipole field will be generated which is precisely aligned with the gyroscope spin-axis. The change in orientation of these fields, as well as the spin-axis, is sensed by the SQUID magnetometers.

In order to attain the superconducting temperatures for the gyroscopes and the SQUIDs, the experiment package will be housed in a dewar filled with liquid helium. As the liquid helium slowly boils-off from the cryogenic system of the spacecraft, the gas must be vented overboard. The resulting thrust can easily be the largest disturbance to the attitude and translational control system. In view of this, the helium could be thought of as a free propellant. Since fuel consumption can not be conserved, the boil-off helium can be vented through proportional thrusters which will control the attitude of the spacecraft by keeping the telescope pointing to Rigel within 70 milliarcseconds. It will also maintain drag-free control along the three translational axes. The drag-free control will essentially null the external disturbance forces arising from atmospheric drag, and from solar and terrestrial radiation. The principle behind drag-free control is that a proof mass inside the spacecraft is shielded from external forces, so that the proof mass follows a nearly ideal gravitational orbit, and a control system activates jets or thrusters to make the spacecraft follow the proof mass. Making the spacecraft drag-free helps in two ways: (1) it reduces gyro suspension forces which result in torques down to a level where relativistic precession can be measured, (2) it reduces errors in orbit determinations needed in analyzing relativity data.

Due to the low rate at which helium gas escapes from a well insulated helium tank, the thrusters must operate in a flow regime vastly different from conventional thruster systems. The development work by Bull[3], Chen[4] and Lee[5] at Stanford University have shown that the helium propulsion system is realistic. Wiktor[6] has worked on the implementation of ultra low flow thruster into the propulsion system for GP-B. The motivation for the present work is to obtain a better understanding of the effect that the plume has on the flow characteristics of the a thruster. A secondary purpose of this investigation is to determine the requirements for modeling the plume, since this is the first attempt at modeling this type thruster.

MODEL DESCRIPTION

Since Gravity Probe B will operate in the rarefied gas regime, traditional computational fluid dynamics cannot be used to model the nozzle flow and exhaust plume. CFD obtains solutions of the mathematical equations that model the processes. When the gas density becomes sufficiently low, the Navier-Stokes equations do not provide a valid model for the rarefied gas. The Navier-Stokes equations depend on the Chapman-Enskog theory for the shear stresses, heat fluxes and diffusion velocities as linear functions of the velocity, temperature and concentration gradients. The formulation for the Chapman-Enskog distribution incorporates the local Knudsen numbers which are the ratio of the local mean free path to the scale lengths of the velocity and temperature gradient. It has been found that errors become significant when these Knudsen numbers exceed 0.1 and continuum theory is useless when they exceed 0.2[7].

Since the Knudsen numbers for the Gravity Probe B thrusters are well above 1; the direct simulation Monte Carlo method was used to model the flow field. The DSMC method developed by G.A. Bird[8], models the gas flow by following the trajectories of a large number of simulated molecules within a region of simulated space. The basic assumption in the method is that the movement of molecules can be decoupled from the collisional process. A probabilistic rather than a deterministic method is used for calculating collisions and is therefore limited to gas flow in which the mean spacing between molecules is large compared to the diameter of the molecules. The time parameter in the model corresponds to physical time in the real flow. All calculations are unsteady, but steady flow may be obtained as the large time average of unsteady flow conditions. The basic assumptions used in the DSMC technique are the same as those in the Boltzmann equation, so that the results are equivalent to a numerical solution of the Boltzmann equation as long as the time step, the cell size and the number of simulated molecules are kept within reasonable limits. The art of setting up the problem is in defining the "reasonable" limits. A DSMC calculation is more like an experiment than a traditional analytical analysis[9].

The results presented in this study were obtained using the axisymmetric/two-dimensional G2/A3 DSMC code written by G.A. Bird [10], which has been modified to run parallel on two processors of a Convex 240 supercomputer. The code employs a variable hard sphere (VHS) model. This is essentially a hard sphere with a diameter that varies with some inverse power of the relative velocity between the molecules in the collision.

DISCUSSION OF RESULTS

The investigation was divided into three test cases: Case 1 modeled only the thruster, while Cases 2 and 3 modeled the thruster with a plume. Case 2 used a plume grid that was designed to capture the flow structure around the nozzle lip. This grid was similar to the one used by Campbell and Weaver[9] in their DSMC nozzle calculations. See Figure 2. Case 3 used a

Cases two and three showed that the addition of the plume increased the static pressure in the thruster plenum. In addition, the plume caused the sonic line to move upstream toward the nozzle throat. On the other hand, the sonic line for the thruster without the plume was located very close to the nozzle exit. This indicates that the thruster plenum is subsonic and any downstream disturbance can affect the entire flow field. This means that the thruster region must be solved each time a new plume grid is employed.

As seen in Table 1, the addition of the plume had very little effect on the total thrust developed by the nozzle. The plume did require more molecules to reach steady state as one would expect. The calculations did show that the coarse grid used in Case 2 allowed the flow field to develop faster than the finer grid used in Case 3. This would allow the investigator to gain a feel for the flow characteristics earlier and be able to make adjustments to the grid. The plume calculations did show that the backflow region develops very slowly. Many different cell sizes and time steps were employed in this region in an attempt to develop this region, but it just took time.

CONCLUSIONS

The structure of the flow of helium through a GP-B micro thruster and into vacuum has been investigated using the Direct Simulation Monte Carlo method. Three cases, the thruster alone, and the thruster with two different plume grids have been compared. The addition of the plume to the calculations does have a definite effect on the upstream plenum flow characteristics. Therefore, the plenum section must be included in each plume calculation due to their interdependence.

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	CASE I	CASE II	CASE III
Total Thrust, N Integrated Thrust, N	0.36483E-05 0.37004E-05	0.36439E-05 0.37029E-05	0.36570E-05 0.37095E-05
Number-Molecules	24,312	51,857	32,529
Number - Samples	100,100	88,400	37,900

Table 1. Comparison of Thrust Calculations.

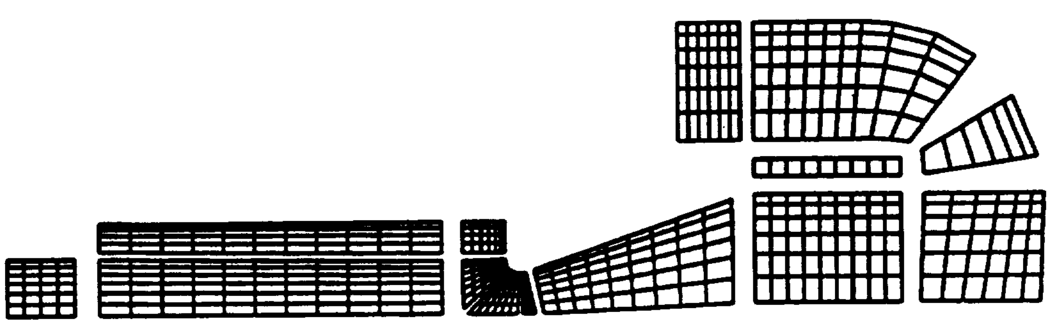

Figure 1. Grid for Case 3 Calculations

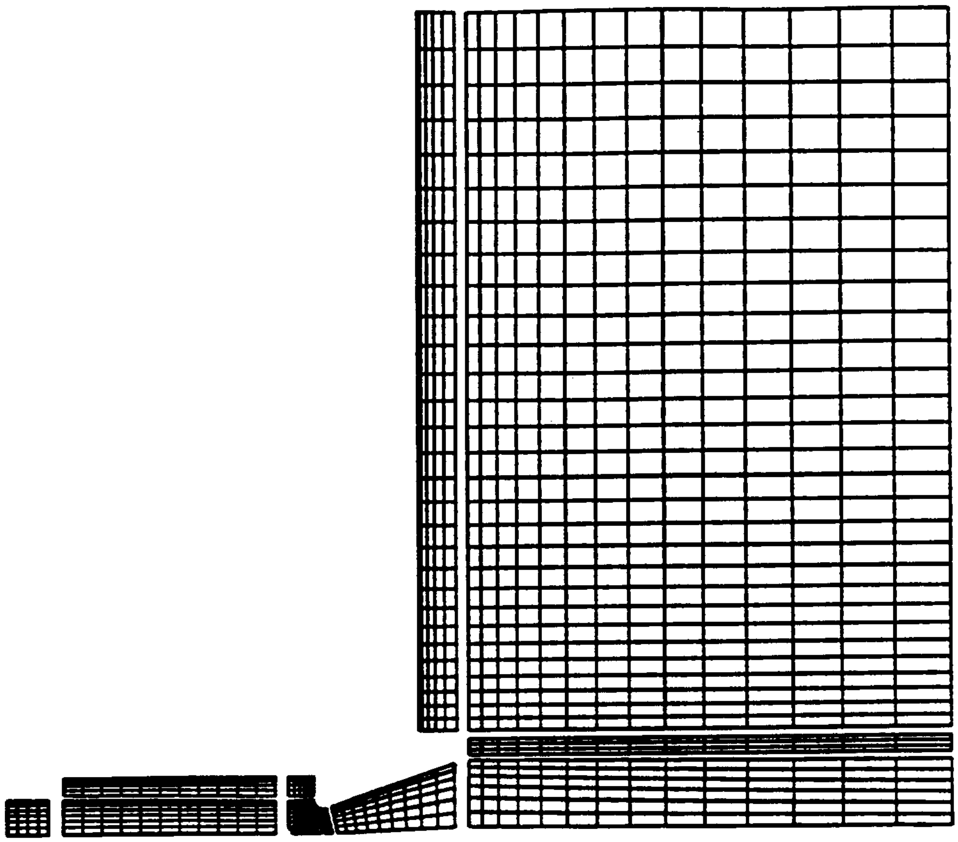

Figure 2. Grid for Case 2 Calculations.