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The objective of this Grant was the development of computational tools to analyze the interactions of Electric Propulsion thrusters with complex structures, such as complete spacecraft, spacecraft in a vacuum tank, or a neighboring formation-flying spacecraft. This entailed substantial extensions and refinements of previous 3D Hybrid PIC code, including adoption of an unstructured tetrahedral grid, mating of this grid to surface grids generated by commercial solid modeling software, integration into the AFRL COLISEUM architecture, allowance for non-quasineutral regions due to obstacles in the plume, streamlining of the collisional operators (no-counter DSMC, MCC option) and allowance of a non-constant electron temperature. Several verifications were run against laboratory data, including plume surveys in our Laboratory of the BHT-200 thruster and a shield-wake experiment of J. Pollard using the larger PPL-90 thruster. This Report summarizes these accomplishments, mainly by reference to the several papers and Theses that were generated, copies of which are attached as a CD.

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INTERACTIONS OF ELECTRIC PROPULSION PLUMES WITH A COMPLETE SPACECRAFT

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Abstract

The objective of this Grant was the development of computational tools to analyze the interactions of Electric Propulsion thrusters with complex structures, such as complete spacecraft, spacecraft in a vacuum tank, or a neighboring formation-flying spacecraft. This entailed substantial extensions and refinements of previous 3D Hybrid PIC code, including adoption of an unstructured tetrahedral grid, mating of this grid to surface grids generated by commercial solid modeling software, integration into the AFRL COLISEUM architecture, allowance for non-quasineutral regions due to obstacles in the plume, streamlining of the collisional operators (no-counter DSMC, MCC option) and allowance of a non-constant electron temperature. Several verifications were run against laboratory data, including plume surveys in our Laboratory of the BHT-200 thruster and a shield-wake experiment of J. Pollard using the larger PPL-90 thruster. This Report summarizes these accomplishments, mainly by reference to the several papers and Theses that were generated, copies of which are attached as a CD.

1. Summary of previously reported work

Two interim Reports were submitted on this Grant: One on Oct. 1, 2001[1], covering the initial four months of work, and one covering the period 10/01/01 – 9/30/03[2]. The second of these included copies of MS Theses by Shannon Cheng, Mark Santi and Yassir Azziz, as well as of three papers generated under this Grant: IEPC-03-134, IEPC-03-140 and AIAA-2003-4873 (Joint Propulsion Conference). The principal developments described in these Reports and referenced papers were:

(a) Development of AQUILA, an evolved hybric PIC plume code that is fully compatible with the COLISEUM interactions framework of the AFRL[3].
(b) Use of GridEx [4] for implementation of an unstructured tetrahedral grid as an extension of a GridEx surface mesh on prescribed objects. Alternatively, use of MGEN[5] for the volumetric grid, as preferred under COLISEUM[6].
(c) Inclusion of a polytropic plasma model $\left(n_e \sim T_e^{\frac{1}{\gamma-1}} \right)$ as an extension of the original isothermal ($\gamma = 1$) model.
(d) Implementation of a no-counter DSMC collision submodel, of special value for situations involving multiple types of collisions.
(e) Implementation of an option to allow embedded non-neutral regions[7], such as behind obstacles or around sharp corners.
(f) Verification of AQUILA against analytical solutions (corner plasma flow, asymptotic plume expansion) and against laboratory Faraday probe measurements[8].
(g) Study using the non-neutral option of the degree of back-filling in the wake of a shield placed on the edge of the plume[7]. This was in preparation for a more detailed study of Pollard's experiment, as reported below.

2. Additional work beyond Sept. 2003.

After publication of J. Pollard and K. Diamant experiments[9] on wake effects due to plates placed 60° and 90° from the axis of the PPL-90 thruster[10], an effort was made to simulate this situation using AQUILA. The results are described in our paper AIAA-2004-3635[11], which is also included in the attached CD. An essential part of any such undertaking is the generation of suitable exit plane profiles to serve as initial conditions for the plume. This was done using our engine code HPHALL, based on J.M. Fife's original work[12], and our paper[11] reports extensively on the resulting profiles (neutral, single and double ion fluxes vs. radius, average axial, radial and aximuthal velocities). For each population, the major source of velocity spread was found to be the existence of two distinct populations, are originating from the nearest portion of the annular chamber, the other from the opposite side (numerically, reflected through the axis of symmetry). These populations are reported and used separately for each radial position on the exit plane. Also, the charge-exchange ion population was split into two, one coming from the thruster, the other formed outside, but ahead of z = 11cm adopted as our plume initial condition (z = 8cm is the actual exit plane). These initial conditions contain a wealth of information that strongly conditions the development of the plume downstream; there is little change that good plume spread predictions could be obtained from crude initializations that do not account for thruster detailed geometry and operating conditions.

The actual simulations were done on a tetrahedral grid adapted to the engine, to the tank used in the experiments (except for a shortening of the tank length beyond the plume shields) and to the experimental shield plates with its leading edge at 60° from the centerline. The non-neutrality option was exercised.

The comparison of current densities in the computations and in the experiment (tank pressure of $1.6 \times 10^{-6}\,Torr$) was reasonable, clearly showing the sharp decreases in the wake. In retrospect, however, the comparison suffered form the use of simulated probes with a narrow acceptance angle, as opposed to the wider angle likely accepted by the actual probes. Thus, the experimental data contain side-glancing impacts from charge-exchange, low energy ions, that are missed by the "numerical probes". The agreement improves with distance downstream of the shield, and the code adequately captures the back-filling of the wake through collisions and ion trajectory deflections due to the negative potential in the wake.

In addition, Ref. [11] shows a parametric sequence of runs varying the tank pressure. There are extensive non-neutral areas behind the plate and the engine when $P_{tk} = 2.7 \times 10^{-7}\,Torr$ but these areas are limited to the immediate vicinity of the plate's back side when $P_{tk} = 1.6 \times 10^{-5}\,Torr$, and are absent at $1.6 \times 10^{-4}\,Torr$.

3. Interactions with the AFRL COLISEUM Team.

Our AQUILA code served as the first test case for the wider framework of COLISEUM, which is expected to accept a diversity of plume and interaction codes as long as they conform to specified interface specifications. Because of this, there were frequent in-depth discussions between the two teams, and these were very useful on both sides, uncovering flaws in COLISEUM specs on the one hand, and suggesting useful improvements in AQUILA on the other. Later on, as the team from Virginia Tech U. began to integrate their own models into COLISEIUM, the AQUILA team was able to act as an advisor and facilitator. Later additions and changes to both HPHall and AQUILA have been communicated to AFRL for integration into COLISEUM.

A brief chronology of the AQUILA-COLISEUM interaction has been prepared for this Report, and is contained in Appendix A.

APPENDIX A
INTERACTIONS WITH COLISEIUM TEAM

2002

Sept. 12-13:

Meeting at MIT with Mike Fife, Doug VanGilder, Matt Gibbons, Advatech.

•Discussed general architecture issues

•Worked on connecting surface to volume mesh (using Prof. Peraire's MGEN work)

-splitting of code libraries

-interfaces between modules (standardize requirements for COLISEUM so AQUILA or VA Tech modules can run with similar input files, grids, etc.)

-discussion about Mark Santi's finite element Poisson solver

-worked on new source specification model

Oct. 3-4:

Meeting at MIT with Mike Fife, Doug VanGilder, Dave Kirtley.

-put to test all work done on integrating AQUILA into COLISEUM – able to run simple case by end of visit.

Nov. 21-22:

Meeting at MIT with Mike Fife, Dough VanGilder, Matt Gibbons, Dave Kirtley.

•While integrating AQUILA into COLISEUM, ran into some fundamental architecture issues, so had this meeting to discuss/resolve issues.

-problem with specifying properties of domain objects – made setting boundary conditions difficult – solved by abstracting into components instead of just materials.

2003

Mar. 3-5:

Meeting at Edwards (after TSIS workshop)

•Mainly working session to continue integration.

•Interaction with VA Tech, getting them up to speed.

Aug. 6-8:

•Air Force had been making their own additions to AQUILA I something called "AQUILA_PLUS" – lots of work on integrating our versions together. Felix Parra (of MIT) was also involved, working on HPHall upgrades and their transition to AFRL.

Nov. 5-7:

Meeting at MIT with Air Force and VA Tech.

•Mostly talked about HPHALL on the MIT end.

•Help with VA Tech integration.

2004

Summer: Shannon Cheng went out to Edwards AFB.

•Worked on JPC paper using AQUILA to do comparison to Pollard shield geometry.

REFERENCES

1. Yearly report for Air Force Grant No. F49620-01-0444, by D. Hastings, M. Martinez-Sanchez and J. Peraire. Oct. 2001.
2. Report for AF Grant No. F49620-01-0444, covering 10/1/01 –09/30/03, by D. Hastings, M. Martinez-Sanchez and J. Peraire.
3. John M. Fife, et al, "The Development of a flexible using plasma interaction modeling system", AIAA-2002-4267, 38th Joint Propulsion Conference, Indianapolis, 2002.
4. W. T. Jones, "An open framework for unstructured grid generation", AIAA-2002-3192, 32nd AIAA Fluid Dynamics Conference, St. Louis, MO, 2002.
5. J. Peraire and K. Morgan, "Unstructured mesh generation for 3D viscous flow", AIAA-1998-3010. 16th Applied Aerodynamics Conference, Albuquerque, NM, June 1998.
6. M. Celik, M. Santi, S.Y. Cheng, M. Martinez-Sanchez and J. Peraire, "Hybrid PIC simulation of a Hall thruster plume on an Unstructured Grid with DSMC Collisions". Paper IEPC-03-134, 28th International Electric Propulsion, Toulouse, France, March 2003.
7. M. Santi, S.Y. Cheng, M. Celik, M. Martinez-Sanchez and J. Peraire, "Further development and preliminary results of the AQUILA Hall thruster plume model". Paper AIAA-2003-4873, 39th Joint Propulsion Conference, Huntsville, AL, July 2003.
8. Y. Azziz and M. Martinez-Sanchez and J. Peraire, "Plasma Measurements on a 200-watt Hall thruster plume". Paper IEPC-03-140, 28th International Electric Propulsion Conference, Toulouse, France, March 2003.
9. Pollard, J.E. and K. Diamant, "Hall Thruster Plume Wake Shield Structure." AIAA-03-5018, 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Huntsville, AL, July 2003.
10. Raitses, Y., L.A. Dorf, A.A. Litvak, and N.J. Fisch. "Plume Reduction in Segmented Electrode Hall Thruster", Journal of Applied Physics 88 (3): 1263-1270 (2000).
11. S.Y. Cheng and Manuel Martinez-Sanchez, "Comparison of Numerical Simulations to Hall Thruster plume shield experiment". Paper AIAA-2004-3635, 40th Joint Propulsion Conference, Fort Lauderdale, FL.
12. Fife, J.M., Hybrid-PIC Modeling and Electrostatic Probe Survey of Hall Thrusters, PhD thesis, Massachusetts Institute of Technology, Department of Aeronautics and Astronautics, September 1998.