

Fundamentals of Electric Propulsion: Ion and Hall Thrusters

Dan M. Goebel and Ira Katz

Jet Propulsion Laboratory
California Institute of Technology

JPL SPACE SCIENCE AND TECHNOLOGY SERIES

Fundamentals of Electric Propulsion: Ion and Hall Thrusters

Dan M. Goebel and Ira Katz

Jet Propulsion Laboratory
California Institute of Technology

JPL SPACE SCIENCE AND TECHNOLOGY SERIES

Fundamentals of Electric Propulsion: Ion and Hall Thrusters

March 2008

The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.



Table of Contents

<i>Note from the Series Editor</i>	<i>xi</i>
<i>Foreword</i>	<i>xiii</i>
<i>Preface</i>	<i>xv</i>
<i>Acknowledgments</i>	<i>xvii</i>
Chapter 1: Introduction	1
1.1 Electric Propulsion Background	2
1.2 Electric Thruster Types	3
1.3 Ion Thruster Geometry	6
1.4 Hall Thruster Geometry	6
1.5 Beam/Plume Characteristics	9
References	11
Chapter 2: Thruster Principles	15
2.1 The Rocket Equation	15
2.2 Force Transfer in Ion and Hall Thrusters	18
2.3 Thrust	21
2.4 Specific Impulse	25
2.5 Thruster Efficiency	27
2.6 Power Dissipation	30
2.7 Neutral Densities and Ingestion in Electric Thrusters	32
References	34
Homework Problems	35
Chapter 3: Basic Plasma Physics	37
3.1 Introduction	37
3.2 Maxwell's Equations	38
3.3 Single Particle Motions	39

3.4 Particle Energies and Velocities	43
3.5 Plasma as a Fluid	46
3.5.1 Momentum Conservation	46
3.5.2 Particle Conservation	48
3.5.3 Energy Conservation	51
3.6 Diffusion in Partially Ionized Gases	54
3.6.1 Collisions	55
3.6.2 Diffusion and Mobility Without a Magnetic Field	60
3.6.3 Diffusion Across Magnetic Fields	66
3.7 Sheaths at the Boundaries of Plasmas	71
3.7.1 Debye Sheaths	73
3.7.2 Pre-Sheaths	76
3.7.3 Child–Langmuir Sheaths	79
3.7.4 Generalized Sheath Solution	81
3.7.5 Double Sheaths	84
3.7.6 Summary of Sheath Effects	86
References	88
Homework Problems	89
Chapter 4: Ion Thruster Plasma Generators	91
4.1 Introduction	91
4.2 Idealized Ion Thruster Plasma Generator	93
4.3 DC Discharge Ion Thruster	100
4.3.1 Generalized 0-D Ring-Cusp Ion Thruster Model	102
4.3.2 Magnetic Multipole Boundaries	105
4.3.3 Electron Confinement	108
4.3.4 Ion Confinement at the Anode Wall	110
4.3.5 Ion and Excited Neutral Production	117
4.3.6 Neutral and Primary Densities in the Discharge Chamber	120
4.3.7 Power and Energy Balance in the Discharge Chamber	124
4.3.8 Discharge Loss	126
4.3.9 Discharge Stability	133
4.3.10 Recycling Behavior	137
4.3.11 Limitations of a 0-D Model	141
4.4 Kaufman Ion Thrusters	142
4.5 rf Ion Thrusters	148
4.6 Microwave Ion Thrusters	158

4.7 2-D Computer Models of the Ion Thruster	
Discharge Chamber	171
4.7.1 Neutral Atom Model	172
4.7.2 Primary Electron Motion and Ionization Model.....	176
4.7.3 Discharge Chamber Model Results	179
References	182
Homework Problems	187
Chapter 5: Ion Thruster Accelerator Grids	189
5.1 Grid Configurations	190
5.2 Ion Accelerator Basics	196
5.3 Ion Optics	200
5.3.1 Ion Trajectories	200
5.3.2 Perveance Limits	204
5.3.3 Grid Expansion and Alignment	206
5.4 Electron Backstreaming	208
5.5 High-Voltage Considerations	216
5.5.1 Electrode Breakdown	217
5.5.2 Molybdenum Electrodes	218
5.5.3 Carbon–Carbon Composite Materials	221
5.5.4 Pyrolytic Graphite	223
5.5.5 Hold-off and Conditioning in Ion Thrusters	224
5.6 Ion Accelerator Grid Life	225
5.6.1 Grid Models	227
5.6.2 Barrel Erosion	230
5.6.3 Pits-and-Grooves Erosion	232
References	235
Homework Problems	240
Chapter 6: Hollow Cathodes	243
6.1 Introduction	243
6.2 Cathode Configurations	248
6.3 Thermionic Electron Emitter Characteristics	251
6.4 Insert Region Plasma	256
6.5 Orifice Region Plasma	270
6.6 Hollow Cathode Thermal Models	281

6.7 Cathode Plume-Region Plasma	283
6.8 Hollow Cathode Life	292
6.8.1 Dispenser Cathodes in Insert Plasmas	293
6.8.2 Cathode Insert Temperature	296
6.8.3 Barium Depletion Model	298
6.8.4 Bulk-Material Insert Life	302
6.8.5 Cathode Poisoning	304
6.9 Keeper Wear and Life	306
6.10 Hollow Cathode Operation	309
References	315
Homework Problems	321
Chapter 7: Hall Thrusters	325
7.1 Introduction	325
7.2 Thruster Operating Principles and Scaling	329
7.2.1 Crossed-Field Structure and the Hall Current	330
7.2.2 Ionization Length and Scaling	334
7.2.3 Potential and Current Distributions	337
7.3 Hall Thruster Performance Models	341
7.3.1 Hall Thruster Efficiency	341
7.3.2 Multiply Charged Ion Correction	345
7.3.3 Dominant Power Loss Mechanisms	347
7.3.4 Plasma Electron Temperature	357
7.3.5 Hall Thruster Efficiency (Dielectric Walls)	359
7.3.6 TAL Hall Thruster Efficiency (Metallic Walls)	363
7.3.7 Dielectric-Wall Versus Metallic-Wall Comparison	364
7.4 Channel Physics and Numerical Modeling	365
7.4.1 Hybrid Hall Thruster Models	366
7.4.2 Steady-State Modeling Results	372
7.4.3 Oscillations in Hall Thrusters	376
7.5 Hall Thruster Life	379
References	384
Homework Problems	389
Chapter 8: Ion and Hall Thruster Plumes	393
8.1 Introduction	393

8.2 Plume Physics	395
8.2.1 Plume Measurements	395
8.2.2 Flight Data.....	396
8.2.3 Laboratory Plume Measurements.....	398
8.3 Plume Models	400
8.3.1 Primary Beam Expansion.....	400
8.3.2 Neutral Gas Plumes	407
8.3.3 Secondary-Ion Generation	408
8.4 Spacecraft Interactions	410
8.4.1 Momentum of the Plume Particles	412
8.4.2 Sputtering and Contamination	413
8.4.3 Plasma Interactions with Solar Arrays.....	415
8.5 Interactions with Payloads	418
8.5.1 Microwave Phase Shift	418
8.5.2 Plume Plasma Optical Emission.....	419
References	422
Homework Problems	424
Chapter 9: Flight Ion and Hall Thrusters	429
9.1 Introduction	429
9.2 Ion Thrusters	429
9.3 Hall Thrusters	440
References	443
Appendices	
A: Nomenclature	447
B: Gas Flow Unit Conversions and Cathode Pressure Estimates	463
C: Energy Loss by Electrons	467
D: Ionization and Excitation Cross Sections for Xenon	471
E: Ionization and Excitation Reaction Rates for Xenon in Maxwellian Plasmas	475
F: Electron Relaxation and Thermalization Times	479
G: Clausius Factor Monte Carlo Calculation	483