

The Design Space of a Micro/Nano-Particle Electrostatic Propulsion System

by

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Aerospace Engineering)
in The University of Michigan
2010

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*“Whether we call it sacrifice, or poetry, or adventure,
it is always the same voice that calls.”*

Antoine de Saint-Exupéry, *auteur et aviateur* (1900-1944)

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Dedication

For my grandfathers (劉鼎錚 and 謝連景), whose sacrifices, guidance, and encouragements made this possible.

乖孫

沐昌敬上

Acknowledgements

At times, the doctoral research process feels like a personal reenactment of Zeno's paradox. If not for the support and contributions by many wonderful people, the finish line would still be just out of reach.

My family has been with me every step of this journey, keeping me humble during times of success and keeping my spirits up during times of trial. This dissertation is a testament to their unwavering love and enduring patience.

I have been privileged to work under the tutelage of my dissertation committee co-chairs, Professors Alec Gallimore and Brian Gilchrist. They have afforded me great academic freedom to explore and find my place academically and professionally. Under their guidance, I have learned — from seeing, doing, and teaching — how to be a researcher and an educator. Their technical expertise, motivational moxie, management acumen, and networking prowess are outstanding qualities that I strive to emulate.

Professors Mike Solomon and Jamie Cutler provided insightful help as members of my dissertation committee, and I look forward to continued collaborations in the areas of micro/nano-particle interactions and spacecraft missions. Dr. Pete Peterson played the ultimately much appreciated role of pushing me out of my existing comfort zone and keeping me focused.

My way through graduate school was funded by both a National Defense Science and Engineering Graduate fellowship and one from the National Science Foundation.

Thanks also to the Shipman Society, whose undergraduate scholarship allowed me to attend the University of Michigan in the first place. The actual research work would not have been possible without initial funding from the NASA Institute of Advanced Concepts and subsequent funding from Dr. Mitat Birkan and the Air Force Office of Scientific Research

Louis Musinski started the NanoFET adventure with me in discovering how “good things come in small packages.” Greg Wagner has been instrumental in crunching the code for our electrostatic simulations on particle charging. Dr. Michael Keidar and Professor Mark Burns provided invaluable help with the liquid NanoFET configuration. I enjoyed working alongside Professor Joanna Mirecki-Millunchick, Desh Mukhija, Inkyu Eu, Andy Di, and David Liaw to bring NanoFET to life.

My mentors (Dave Morris, Chris Deline, Hannah Goldberg, and Rafael Ramos) at the “4 Guys Office” showed me the ropes (or space tether, as it were). Thanks for always being willing to lend a sympathetic ear.

I have had the pleasure of working with and learning from a brilliant group of lab mates at the Plasmadynamics and Electric Propulsion Laboratory. Tim Smith, Mitchell Walker, Dan Herman, Josh Rovey, Allen Victor, Jesse Linnell, Prashant Patel, Dave Kirtley, Dan Brown, and Bailo Ngom set high standards to follow. Ricky Tang, Mike McDonald, Ray Liang, Adam Shabshelowitz, Laura Spencer, and Roland Florenz all broadened my knowledge regarding the nature and uses of plasmas. Special thanks to the following lab mates: Bryan Reid and Sonca Nguyen for pacing me through coursework and the qualifying exams, Kristina Lemmer for forging me into a true Wolverines fan, Robbie Lobbia with his many fruitful suggestions of neat ideas to explore, David Huang

for his Jedi-like laboratory skills and reassuring company during laser testing, and Rohit Shastry for keeping me sane, entertained, and well-fed with late night, fourth-meal runs.

Denise Phelps, Suzanne Smith, Cindy Enoch, and Michelle Shepherd were accommodating guides as I navigated through the labyrinth of university bureaucracy. The aero techs (Tom Griffin, Dave McLean, Chris Chartier, and Terry Larrow) were always willing to chat about how to make things work better (or at all) and to instruct me on good machining and electronics practices; Robb Gillespie and John Eder played similar roles at the Space Physics Research Laboratory. Kimberly Appel and Dr. Rob Howard at the Solid State Electronics Laboratory introduced me to the intricacy of MEMS, whereas the staff at the Electron Microbeam Analysis Laboratory taught me how to see them. Professors Pete Washabaugh and Nilton Renno were always there with a timely loan of needed test equipment.

I would be remiss if I did not acknowledge the important role played by the Student Space Systems Fabrication Laboratory (S3FL), the care of which ate up my free time and led to many a sleepless night. We have grown together, from the dark, post-*Columbia* days with Icarus and FEGI, through the endless permutations of FENIX and TSATT, to a bright, promising future with the NanoSat Pipeline. S3FL gave me the opportunity to hone my leadership and management skills, indulge in my teaching interests, train a generation of enthusiastic and creative engineers, and inspire pre-college students to pursue careers in the STEM fields.

My S3FL NanoBLUE and ZESTT teams, with the support of directed study students, allowed me to experience, vicariously, the thrill of conducting research in zero-g; thanks to NASA's Reduced Gravity Office for providing the flight opportunities.

Bonnie Bryant and the Michigan Space Grant Consortium, the Women In Science and Engineering office, Jennifer Wegner and the College of Engineering, and Mike Lee and the Wilson Student Team Project Center provided critical financial, logistical, and manufacturing support for the microgravity projects.

Finally, to my trio of talented CEs (Ashley Smetana, Theresa Biehle, and Brittany Drenkow), my heartfelt thanks for your hard work, long hours, and tireless dedication. I have learned as much from you as you ever did from me. Together, we have all become wiser.

Finally, one that does not receive thanks is Microsoft, whose half-hearted implementation of software for Macs did me absolutely no favors during the dissertation writing process.

Foreword

One calm, summer morning just east of the Rockies, a small, boxy payload left my hands and hitched a ride skywards aboard a weather balloon. By the time it landed back on *terra firma* several hours later, the balloonsat's camera eye had climbed far above the rich browns and vibrant greens of the Great Plains, floated through wispy tendrils of white, sun-split clouds, and marveled at the sweep of Earth's blue horizon against the inky blackness. "Once you have tasted flight, you will forever walk the earth with your eyes turned skyward; for there you have been, and there you will always long to return," Leonardo da Vinci wrote half a millennium ago. Daydreaming about the images from the flight, I could not have agreed more.

Throughout history, space — with its allure of the mysterious unknown and vast potential — has stimulated human imaginations and inspired spectacular scientific and technical advancements: We have sought to compose the music of the spheres and have listened for signals from beyond; we have dreamed of touching the face of heaven and have touched down on other worlds. Space prompts the human spirit to shed its terrestrial constraints, proposes prospects for alleviating resource and environmental depletion on Earth, and promotes the unifying awareness that despite our differences, all humans are members of the same species in our tiny blue cradle.

But space is a challenging place to traverse. Not only can paths be steeply uphill against gravity, but the speed police are also always vigilant. To enhance our ability to

achieve present goals and enable future aspirations in space, improved propulsive capabilities are both desirable and necessary.

This dissertation is a humble contribution to the field of space propulsion. The following pages showcase a novel, nanotechnology-based electric propulsion system that may, in the near future, permit the use of the infinitesimal to explore the infinite. American rocketry pioneer Robert Goddard once remarked “the dream of yesterday is the hope of today and the reality of tomorrow.” This work hopes to motivate the realization of such a dream, borne on summer winds towards the waiting stars.

T. Liu

March 5, 2010



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List of Symbols

A	=	array area
a_I	=	inertial acceleration
a_I^*	=	inertial acceleration threshold to overcome van der Waals forces
B	=	integrated field enhancement factor
Bo	=	Bond number
Bo^*	=	critical Bond number
C_{PZT}	=	piezoelectric capacitance
D	=	gate orifice diameter
D^*	=	critical gate orifice diameter
d	=	particle diameter
E	=	applied electric field
E_0	=	background electric field
E_c	=	background charging electric field
E_L	=	liftoff electric field threshold
E_{max}	=	maximum allowable particle surface electric field
E_{min}	=	electric field threshold for liquid surface instability
E_s	=	particle surface electric field
F	=	force
F_E	=	electrostatic force
F_G	=	gravitational force
F_I	=	inertial force
F_V	=	van der Waals force
f	=	piezoelectric frequency
g	=	gravitational acceleration
g_0	=	sea-level gravitational acceleration
H	=	diode separation distance

H_A	=	Hamaker constant
h_c	=	capillary height
I_b	=	beam current
I_d	=	density specific impulse
I_{rms}	=	root-mean-squared piezoelectric current
I_{sp}	=	specific impulse (subscripts: h for hollow particles, s for solid particles)
I_t	=	total impulse
K	=	kinetic energy
L	=	characteristic length of system
l	=	slot orifice length
m	=	particle mass (subscripts: h for hollow particles, s for solid particles)
m_0	=	rocket wet mass
m_p	=	propellant mass
N	=	number of emitters
P	=	thruster input power
P_{PZT}	=	piezoelectric power dissipated
P_T	=	thrust power
P_{T0}	=	thrust power for single emitter
R	=	emitter array pitch
R_d	=	perturbation radius
r	=	radial position
q	=	particle charge
q_0	=	saturation isolated-particle charge in uniform background electric field
q_1	=	saturation isolated-particle charge in planar diode
q_{1p}	=	saturation proximal-particle charge in planar diode
q_2	=	saturation isolated-particle charge in gated diode
q_{2p}	=	saturation proximal-particle charge in gated diode
q_3	=	saturation isolated-particle charge in gate-sieve diode
S	=	Gaussian surface
T	=	thrust
T_0	=	thrust for single emitter

t	=	time
$t_{99\%}$	=	pulse settling time to 99% of nominal value
t_G	=	gate electrode thickness
t_T	=	characteristic Taylor cone formation time
t_{rise}	=	pulse rise time
t_w	=	shell wall thickness
U	=	potential energy
U_V	=	potential energy due to van der Waals interaction
u_e	=	effective exhaust velocity
V_A	=	acceleration potential
V_{PZT}	=	peak-to-peak piezoelectric voltage bias
V_c	=	charging potential
V_o	=	operating voltage
V_p	=	propellant volume
w	=	slot orifice width
x	=	displacement
x_{PZT}	=	piezoelectric peak-to-peak oscillation amplitude
y_d	=	perturbation height
z	=	particle protrusion height from sieve plane
z_s	=	surface-to-surface separation distance
z_{s0}	=	closest surface-to-surface separation distance
\dot{m}	=	propellant mass flow rate
\dot{m}_0	=	propellant mass flow rate for single emitter
q/m	=	specific charge (subscripts: h for hollow particles, s for solid particles, max for theoretical maximum)
Δt	=	time increment
ΔV	=	velocity increment
A	=	surface normal vector
D	=	electric displacement field

\mathbf{E}_s	=	particle surface electric field
\mathbf{n}	=	surface normal unit vector
α_0	=	net particle charging factor
α_{10}	=	planar-diode isolated-particle charging factor
α_{1p}	=	planar-diode proximal-particle charging factor
α_{1p0}	=	net planar-diode proximal-particle charging factor
α_{20}	=	net gated-diode isolated-particle charging factor
α_{21}	=	gated-diode isolated-particle charging factor
α_{2p}	=	gated-diode proximal-particle charging factor
α_{2p0}	=	net gated-diode proximal-particle charging factor
α_{30}	=	net gate-sieve-diode isolated-particle charging factor
α_{32}	=	gate-sieve-diode isolated-particle charging factor
α_A	=	emitter packing factor
α_{isp}	=	specific impulse enhancement factor
$\alpha_{q/m}$	=	specific charge enhancement factor
β	=	field enhancement factor
β_k	=	knife-edge expansion angle
γ	=	surface tension coefficient
γ_c	=	image charge factor
δ_{ij}	=	Kronecker delta
ϵ	=	permittivity
ϵ_0	=	permittivity of free space
$\zeta_{D,d}$	=	normalized gate orifice diameter
$\zeta_{D,H}$	=	gate aspect ratio
$\zeta_{H,d}$	=	normalized diode separation distance
$\zeta_{R,d}$	=	normalized proximal distance
$\zeta_{t,d}$	=	normalized shell wall thickness

$\zeta_{z,d}$	=	normalized particle protrusion height
η_{misc}	=	miscellaneous thrust efficiency effects
η_{PZT}	=	thrust efficiency effect from piezoelectric operations
η_p	=	particle packing factor
$\eta_{q/m}$	=	specific charge factor
η_T	=	thrust efficiency
η_θ	=	plume divergence efficiency
θ	=	polar angle
θ_c	=	liquid equilibrium contact angle
λ	=	wavelength
ξ_p	=	propellant mass fraction
ρ	=	effective mass density
ρ_0	=	mass density of ambient environment
ρ_c	=	space charge density
$\rho_{\text{H}_2\text{O}}$	=	water mass density
ρ_h	=	hollow particle shell mass density
ρ_l	=	liquid mass density
ρ_s	=	solid particle mass density
σ	=	electrical conductivity
τ_c	=	characteristic charge transfer time
ϕ	=	electric potential

Abstract

The Nanoparticle Field Extraction Thruster (NanoFET) is a micropropulsion technology that electrostatically charges and accelerates micro- and nano-particles to generate thrust. Designed in a flat-panel configuration for scalability to different spacecraft power levels, NanoFET is anticipated to provide a large propulsive envelope capable of accomplishing a range of missions not currently possible with a single propulsion system. In addition, NanoFET also has potential applications as a generalized nano-particle accelerator for terrestrial uses in the fields of materials processing, environmental remediation, and biomedicine.

Three key challenges facing NanoFET's development are:

1. How can specific charge be controlled to meet propulsive performance targets with reasonable operating potentials?
2. How can inter-particle cohesive and particle-electrode adhesive forces be overcome to permit charged particle extraction?
3. How can technical and integration risk be mitigated to advance NanoFET's technology readiness level?

2-D, axisymmetric, finite-element simulations were conducted of particles undergoing electrostatic charging in diode configurations. Maximum charging was obtained for extractor gate aspect ratios (i.e., gate orifice diameter to diode separation) less than unity and for emitter-to-emitter spacings greater than five particle diameters.

Thin-shell particles are proposed as an attractive means of maximizing specific charge by reducing the effective particle mass density.

Piezoelectrics were considered as an efficient means of applying inertial forces to aid with overcoming cohesive and adhesive forces, which are also mitigated by nanometer-scale surface coatings that increase the effective surface-to-surface separation. The piezoelectrics in NanoFET's feed system are expected to set the characteristic time scale of thruster operations and provide for throttleable mass flow rates and precise impulse bits. Together with throttling the operating voltage, NanoFET is a variable specific impulse thruster (e.g., 100-900 s) with expectations of high thrust-to-power (e.g., $> 1 \text{ mN/W}$) and thrust densities (e.g., $\sim 1 \text{ mN/cm}^2$) when used at modest specific impulses.

Prototype micro-particle extractors are in the process of being tested for both dry and liquid-suspended propellants, the latter for terrestrial applications. Modeling and experimental results are promising and recommend NanoFET for continued development.