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

by

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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)

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

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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

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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

$\mathbf{A}$ = surface normal vector

$\mathbf{D}$ = 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

ρ_{H2O} = 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 mN/W) and thrust densities (e.g., ~1 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.