Hall Effect Thrusters

Eduardo Ahedo
1. Past and Present of HET
2. Principles of operation
The device in operation

- anode & gas injector (at back of chamber)
- Cathode/neutralizer
- electron beam
- thruster
- Xenon-ions beam

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HET was invented 50 years ago

- HETs were invented in the early 1960s simultaneously in USA and USSR

USA early prototype (Janes, 1966)

USSR early prototype (Morozov, 1972)
A Soviet achievement

- In 1971, the USSR launched the first HET (SPT-50, 20 mN) in Meteor Spacecraft
- Around that time, USA abandoned research on HET (favoring research on the Gridded Ion Thruster, GIT)
- In the next two decades, USSR launched several missions using HET for satellite station keeping
- This activity was totally ignored by the rest of the world
In search of lost time

- USSR fall and subsequent diaspora of scientists unveiled the existence of that successful engine
- Joint ventures and intensive research programs on HET were then initiated in USA, Europe, and Japan.
- Ten years later, first HETs were tested in flight by USA and Europe.

- First USA ComSat using HET was launched by SSLoral in 2004. Still in operation.
- Today, more than 50% of SSLoral satellites are equipped with HET.
The SMART-1 mission

- This ESA satellite was the first mission ever using HET as primary space propulsion, achieving (a) Earth-orbit raising, (b) Earth-to-Moon transfer, (2) Moon-orbit operations
- The single PPS-1350 (1.3kW, 70mN) used just 82 kg of Xe during 10 months of firing for the 2-year mission
Rocket and mission magnitudes

- In-space propulsion is needed to change/provide spacecraft velocity and orientation: \( \Delta V = \text{sum of velocity changes needed} \)
- Total impulse = \( M_{\text{spacecraft}} \times \Delta V \)

- Rocket propulsion is based on action/reaction forces
- Thrust \( F \) = action force of plasma jet on spacecraft
- Specific impulse: \( I_{sp} \approx \frac{M_{\text{spacecraft}} \times \Delta V}{M_{\text{propellant}}} \)
- Onboard electric power \( P \)
- Propulsive efficiency,
  \[ \eta = \frac{P_{\text{useful}}}{P} \approx \frac{F \cdot I_{sp}}{2P} \approx 0.1 - 0.8 \]
  - \( \eta \) measures the ‘quality’ of the thruster

Note: Isp can be expressed in sec or in km/s; last one, less familiar but more convenient
The propulsion dilemma

- Thrust vs $I_{sp}$: $$(F/P) \times I_{sp} = 2\eta \approx 1$$

- Higher $I_{sp}$ (i.e. lower $F/P$) implies:
  - Lower acceleration ($\propto F/P$)
  - Longer thruster firing ($\propto P/F$)
  - Lower propellant mass ($\propto 1/I_{sp}$)
    → Lower launching cost

- Minimization of launching cost requires to consider, in addition,
  1. weight of the thruster system,
  2. constraints on firing duration

  ⇒ There is an optimal $I_{sp}$

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New: dual propulsion mission for GEO satellites

1. GTO-GEO orbit raising, at maximum thrust
2. Station Keeping, at maximum Isp

Qualification of dual-mode thruster is very challenging
The all-electric spacecraft

- Conceived by Boeing in 2012 is being the new trend
- Several platforms are being designed and flown
- Strong competition between GIT and HET
  - HET is better positioned (currently)
‘Mid-class’ HET vs the ‘up-class’ GIT

- GIT is the jewel of the large EP family. It has
  - the highest efficiency
  - the longest duration
  - the highest specific impulse
  - the lowest beam divergence
  - a successful flight history (HET too)

- But GIT (compared to HET) is
  - much more complex to manage electrically
  - heavier → which can spoil the $M_{\text{propellant}}$ saving
  - more expensive
  - less flexible operationally?

- HET is dominating space market…and even Mars race
High-power HET for exploration

Indeed a HET!

Ion Thruster Prototype Breaks Records in Tests, Could Send Humans to Mars

By Tereza Pultarova, Space.com Contributor | October 13, 2017 07:00am ET

NASA X3
Nested HET, 102kW,
5.4 N, 2000s-Isp,
Low-power HET for Near-Earth missions

- Low-to-mid power HET are being considered for new applications:
  - Constellations of 100s satellites
  - Galileo GPS 2nd generation
  - Earth Observation
- Issue: HET loses efficiency below ~100W
1. Past and Present of HET
2. Principles of operation
Production and acceleration processes

- In GIT: (1) production, (2) acceleration, and (3) beam neutralization regions are very clearly separated
- In a HET, the same 3 regions exist but they are partially overlapped
- These coupled processes must be considered together
HET operation basics

- An electric source set discharge voltage (~300-500V) between (a) anode and (b) electron-emitting cathode
- Cathode-emitted electron current splits itself into outward-bound and inward-bound electron beams
- Inward-bound electrons ionize neutral gas
  - Born ions are accelerated outwards by electric field, creating an ion beam
  - Born electrons move inwards and are collected by anode
- Outward-bound electrons current neutralizes ion beam current.

![Diagram of HET operation](wikipedia)
HET operation basics

- How the plasma manages by itself to split the emitted electron current, such that $I_{\text{electron-out}} = I_{\text{ion}}$?
- Net electric current is not zero $\Rightarrow$ thruster gets charged electrically $\Rightarrow$ surrounding electric potential field is modified, in order to restore zero electric current

- How do we create a radial magnetic field in the annular chamber?
  - With coils and ferromagnetic material
  - Some HET use permanent magnets
Why a radial magnetic field is needed

- **Without B-field:** free electron acceleration by E-field
  - $t_{residence} (10^{-2} \mu s) << t_{ionization} (1 \mu s) \Rightarrow$ no gas ionization

- **With applied B-field:** composed electron motion
  1. Electron gyromotion around B line $\rightarrow$ magnetic confinement
  2. ExB azimuthal drift $\rightarrow$ main role of E-field on electrons
  3. Collisional axial drift $\rightarrow$
     - the way to advance axially
  4. Radial bouncing between walls
     $\rightarrow$ electrostatic confinement
  - $t_{residence} (10 \mu s) >> t_{ionization} (1 \mu s)$
    $\Rightarrow$ plasma is created!

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Why ions are not magnetized?

- Applied magnetic field is 200-400 gauss
  - Earth’s magnetic field ~ 0.5 gauss
  - Tokamak magnetic field ~ 10000 gauss = 1 tesla

- Ions are practically unaffected by magnetic field
  - This is done on purpose!
  - They move axially practically free, accelerated by E-field

- How can it be?
  - The effect of the B-field is proportional to $\sqrt{m_{\text{particle}}}$
  - $\frac{m_{\text{xenon}}}{m_{\text{electron}}}$ ≈ 240500
  - A magnetic field 100-300 times larger would be needed to magnetize ions (as in a tokamak)
How thrust is achieved in HET

- The action-reaction force between HET and plasma beam is magnetic.
- The principle is the same of the repelling forces between two counterstreaming rectilinear currents.
- Here, these currents form loops.
  - In HET: those forming the coils.
  - In beam: the continuous supply of azimuthal electron currents.

\[
F = I_1 \times B_2 \\
F = I_2 \times B_1
\]
The roles of self-adjusted electric field

- Electric field fulfills Gauss law:
  \[ \varepsilon_0 \text{div} \vec{E} = \rho_{\text{elec}} = \rho_i + \rho_e \]
- \( \vec{E} \) acts in order to minimize \( \rho_{\text{elec}} \), resulting in:
  - Near equal (but opposite) electric charges: \( \rho_e \approx -\rho_i \)
  - Near equal (but opposite) electric fields: \( \rho_e \vec{E} \approx -\rho_i \vec{E} \)
  - Negligible net effect of \( \vec{E} \) on momentum of plasma as a whole (i.e. electron/ion pairs): \( (\rho_e + \rho_i)\vec{E} \approx 0 \)
- \( \vec{E} \) is the agent helping the electron-to-ion energy transfer

- Negligible net effect of \( \vec{E} \) on momentum of plasma as a whole (i.e. electron/ion pairs): \( (\rho_e + \rho_i)\vec{E} \approx 0 \)
How thrust is related to ion momentum

- $E \times B$ drift expresses Lorentz force equilibrium (per electron):
  \[ 0 \approx -eE_z + ev_{\theta e} B_r \]

- Momentum gain (per ion):
  \[ m_i \frac{Dv_{zi}}{Dt} \approx eE_z \]

- Adding for an ion/electron pair
  \[ m_i \frac{Dv_{zi}}{Dt} \approx e v_{\theta e} B_r \]

- Reaction force = Magnetic force on electrons = Electric force on electrons = Electric force on ions = Momentum gain of ions
Why HET is less efficient & durable than GIT

- **Penalty in efficiency** comes from
  1. Larger plume divergence, due to
     - Lower discharge voltage
     - More spread out plasma production
     **Difficult to improve.**
     **Plume-spacecraft interaction is a major concern**
  2. Larger particle & energy losses at chamber walls, due to
     - Hotter plasma in HET
     - No magnetic shielding at lateral walls
     **Consequence of this:**
     - **Penalty in lifetime** due to
       - Wall sputtering
   **New HET designs look for magnetic shielding of walls**
Novel HET designs

- More complex magnetic topologies, try to simultaneously
  a) limit axial electron transport
  b) shield chamber walls magnetically [i.e. limit radial transport]

![Aerojet, XR5](image)

**Unshielded (US)**
- Magnetic Field Line
- Easy access to wall
  - Anode
  - Inner wall
- Weaker B: easier route for electrons

**Magnetically-Shielded (MS)**
- Magnetic Field Line
- Difficult access to wall
  - Anode
  - Inner wall
- (Mikellides, 2013)
Are HET physics well-enough understood?

- **NO!** Central phenomena affecting HET performances are insufficiently understood
- This precludes development of predictive numerical codes
- These codes are highly needed to reduce costs of design, development, and qualification of new long-life (3-4 years), multi-mode HETs
- A large worldwide research effort, covering from theory to testing, is under way to achieve these predictive tools
Thank you for your attention

is actively researching, within H2020 CHEOPS project, in HET physics modeling & development of reliable simulation codes.