Air-Breathing Electric Propulsion

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Classification of air-breathing propulsion

- Beamed-energy propulsion
- Ramjet / Scramjet
- In-space propulsion
Classification of air-breathing systems

• Ramjet / Scramjet
  – (Supersonic) air-breathing jet engine
  – Fuel-efficient ascent to mesospheric altitudes and half-orbital velocity

• Air-breathing beamed-energy propulsion
  (see lectures 10/26 and 11/02)
  – Laser or microwave propulsion
  – Fuel-efficient ascent to orbital altitudes

• Atmosphere-breathing in-space propulsion
  – Use of atmospheric residual gases in spacecraft propulsion
  – Reduction of atmospheric drag in lower altitudes
  – Extension of in-orbit lifetime
Orbit decay without propulsion

• Orbit decay of satellites is driving factor for lifetime in LEO

Ballistic coefficient
\[ \beta = \frac{m_{SC}}{C_D \cdot S} \]

- \( \beta \) is high:
  - high momentum
  - low drag
- \( \beta \) is low:
  - low momentum
  - high drag

For altitudes lower than 400 km, orbit decay overtakes commercial benefit

Example for LEO spacecraft

- **GOCE (ESA)**
  - 260 km orbit
  - Designed lifetime:
    - 20 months
  - Actual lifetime:
    - 56 months
    - Lower solar activity than expected
  - Use of fuel-efficient ion thrusters
  - Very high ballistic coefficient to extend possible lifetime

\[
\beta = \frac{1077 \text{ kg}}{3.7 \cdot 0.9 \text{ m}^2} = 323 \frac{\text{kg}}{\text{m}^2}
\]

- Reason for end of life:
  - Fuel depletion, decayed

www.esa.int
Purpose of air-breathing propulsion

• Extension of satellite lifetime in LEO for orbit altitudes less than 400 km
  – Increase data outcome of Earth observation satellites, scientific platforms, reconnaissance/espionage satellites, etc.
  – Increase profit margin for commercial satellites
• Enable scientific missions in very low Earth orbits (VLEO) of less than 160 km in altitude

Air-breathing space propulsion
**Atmosphere**

- Thermosphere and especially the VLEO are scientifically interesting due to strong gradients in physical profile.
- Satellites in orbits closer to Earth could enable new missions:
  - Earth observation
  - Scientific applications
  - Military use
  - ...
Atmospheric properties

• Necessary properties for design of spacecraft and breathing propulsion system
  – Mass density (translates to eventual usable mass flow rate and drag force)
  – Temperature, conductivity (influence on collector and satellite design)
  – Atomic, ionic, and molecular species; molar composition (usage as propellant)
  – ...

• De facto standard model for description of the atmospheric properties is the 1975 International Standard Atmosphere (ISA) with amendments in 1985 and 1997
Atmospheric models (a brief review)

1960
- Jacchia model (1965, 1971)
  - Total density as f(h)
  - Temperature as f(h)

1970
- MSIS (1977)
  - Species composition included (N₂, O₂, O, He, Ar, and H)
  - 120-150 km

1980
- MSIS-83
  - 80-220 km

- MSIS-86
  - Atomic nitrogen added

- MSISE-90
  - Revision for 120 km and below (down to mesosphere)

1990
- Current most accurate model for total density

1990
- Current most accurate model for composition

2000
- JB2006
  - Improved density description
  - New temperature as f(h)

- JB2008
  - Even better temperature function

- NRLMSISE-00
  - Anomalous oxygen
  - Improved modeling

- Both models adapted to the 2008 ECSS standard ECSS-E-ST-10-04C
Atmospheric properties

- Atmospheric density as a function of altitude and solar activity
- Several parameters affect density
  - Location
  - Time of year
  - Solar activity

![Graph showing atmospheric density as a function of altitude with different solar activity levels: Low, Moderate, High (short term), High (long term).]

ECSS-E-ST-10-04C
Composition of species

- Strong gradients of temperature and variation of solar radiation yield distribution of species over altitude
- For most orbit altitudes residual air consists of molecular nitrogen and atomic oxygen
- Negligible degree of ionization

![Graph showing composition of species over altitude](image)
Atomic density

- Influence of solar activity on densities of individual species

![Graph showing atomic density variation with altitude for low, moderate, and high solar activities](image-url)
Consequences for the satellite

- Atmospheric drag force imposed on satellite

\[ F_D = \frac{1}{2} \rho \cdot v^2 \cdot S \cdot C_D \]

\( F_D \) ... Drag force
\( \rho \) ... Air density
\( v \) ... Orbital speed
\( S \) ... Cross-sectional area
\( C_D \) ... Drag coefficient

\[ v \approx \sqrt{\frac{GM}{r}} \]

\( v \) ... Orbital speed
\( G \) ... Gravitational constant
\( M \) ... Earth’s mass
\( r \) ... Orbit radius

Orbital speed
Drag coefficient

Figure 3.5: Coefficient of Drag Values: sample \( c_D \) values [RD8]

Drag coefficient

• Drag coefficient is influenced by several parameters
  – Atomic oxygen can adhere to surfaces altering their physical properties
  – Temperature changes can affect material characteristics of outer surfaces
  – Long, slender spacecraft design increases drag coefficient due to friction on the side walls (e.g., GOCE had a drag coefficient of 3.7)
  – Solar arrays and other hardware features affect drag
Drag force

- Resulting drag force (at mean solar activity; for $C_D = 2.2$)

- Orbit decay as a result of partial drag compensation
Conclusions from atmosphere analysis

• Obviously, as size of the satellite decreases, drag force necessary to be compensated decreases as well
• Depending on altitude and targeted lifetime, propellant necessary to overcome the total drag force might be small enough to be carried on board of the satellite
• Resulting from an ESA study, application of air-breathing technology to satellites in orbits above 250 km is not competitive with „conventional“ electric propulsion (propellant break-even point)
System design for air-breathing propulsion

- Air-breathing propulsion system requires more than just a thruster
  - **Intake** to collect necessary mass flow and pre-compression
  - Accumulation and further compression in the **S/C core**
  - **Thruster** suitable to handle atmospheric gases

![Diagram of system design for air-breathing propulsion]

(a) Air-Intake Simple Cone Concept.  
(b) Air-Intake By-Pass Concept.
Collector system

- Collector is necessary to gather propellant from residual atmosphere to yield a mass flow rate for the thruster
- Due to low degree of ionization, electromagnetic collector systems can be discarded
- Mechanical system has many parameters
  - Width, length, material, wall temperature, ...
  - Numerical simulation (e.g., DSMC PIC) essential in design process
- Performance values:
  - Compression ratio
    \[ p_{\text{prop}} / p_{\text{in}} \]
  - Collection efficiency
    \[ \dot{m}_{\text{prop}} / \dot{m}_{\text{in}} \]

Figure 5: Air-Intake from Fujita's 2004 paper.

IV. Balancing Model

A. Introduction

In this Section a simple, analytical model for the evaluation of a generic RAM-EP Air-Intake configuration is presented. The generic design becomes obvious when comparing the introduced designs, where an intake section collects the particles with free stream conditions and guides them into the propulsion system. In the context of this model, the intake section is followed by a chamber section in which it is assumed that all particles have already gone through wall collisions and, thus, have only a thermal movement with regard to the wall temperature left. By this, the only particle flows directed out of the chamber are due to thermal diffusion. One flow back through the intake with its desirably low transmittance probability, and another flow through the outlet. The representation of the outlet flow strongly depends on the specific configuration. For the JAXA’s design, it is the flow passing through the thruster grids, increased by the acceleration provided by them. In general, a feeding system and the thruster itself follows. By balancing these particle flows, the conditions in the separate sections can be estimated.

B. Assumptions

The basic assumptions for the analytical model are following the nomenclature in Fig. 6:

Free Stream Condition
- \( p_{\text{in}}, n_{\text{in}}, T_{\text{in}}, v_{\text{in}} \)
Intake
- \( \dot{N}_{\text{intake}_1}, \dot{N}_{\text{intake}_2} \)
Control Volume, Chamber
- \( p_{\text{ch}}, n_{\text{ch}}, T_{\text{ch}}, v_{\text{ch}} \)
Outlet
- \( \theta_{\text{out}}, \dot{N}_{\text{out}} \)

\( A_{\text{in}} \) and \( A_{\text{out}} \) are the respective cross sections for the inflow and the outflow representing those of the chamber section. The parameters of the incoming flow are known: number density \( n_{\text{in}} \) (or pressure \( p_{\text{in}} \)), flow temperature \( T_{\text{in}} \) and free stream velocity \( v_{\text{in}} \). \( \theta \) is the transmittance into a specific direction through a single structure, indicated in the subscript, and \( \dot{N}_{\text{intake}} \) is the fraction of particles which pass through the exit section against the amount of particles which passed through it.

Figure 6: Balancing Model Scheme.
Air inlet examples

- 1\textsuperscript{st} comprehensive study conducted at JAXA (Nishiyama/Fujita)
  - ABIE: air-breathing ion engine
  - Variation of parameters to analyze possible performance
  - Compression ratio derived to be around 100-200
  - Optimum collector design depends on altitude
Air inlet examples

- Subsequent studies at ESA and Busek (US company)

![Diagram showing pressure for different aspect ratios](image)

Pressure for different aspect ratios

- about 1 mPa achievable

![DSMC Code Predictions](image)

![Conceptual diagram of inlet process](image)
Air inlet examples

• Study at U Stuttgart (Germany)
  – Rarefied flow computation with coupled 3D full-PIC DSMC
  – Numerical analysis necessary as incident flow is not a continuum flow
  – Geometrical variation can yield optimum collection efficiency
  – Addition of straws in the intake flow increases efficiency
  – Tracking of individual species feasible
Air inlet – what to expect

- **Compression ratio**
  - Achievable results around 100-200
  - Typical $p_{\text{prop}}$ around 1 mPa
- **Collection efficiency**
  - Typical values in the order of 40 %
- **Experimental verification by upper atmosphere simulators**
Consequences for the satellite

- As collection efficiency decreases, thrust and, hence, exhaust velocity have to increase to compensate the drag force.

\[ c_e \geq \frac{v \cdot C_D}{2 \cdot \eta_c} \]
Possible propulsion options

• Chemical propulsion
  – Maximum exhaust velocity of 4.5 km/s far less than requirement
  – No favorable reaction with molecular nitrogen

• Electric propulsion (see also lecture 10/19)
  – Electrothermal (resistojet, arcjet)
  – Electrostatic (ion thruster, Hall thruster)
  – Electromagnetic (MPD, PPT)

• Other concepts
Electrothermal propulsion

- Resistojets and arcjets are basically capable of using atmospheric propellants, but erosion due to oxygen will decrease the lifetime of thruster dramatically.
Electrostatic propulsion - Ion thruster

- ABIE (JAXA, 2003)
  - Aimed for 150-200 km of altitude
  - Microwave discharge ion thruster
  - Operation at low injection pressures of 5 to 500 mPa
    (additional compression required)
  - T/P around 10 mN/kW
  - Size would require a compensation of 50 to 100 mN of drag
    significant power requirement
Electrostatic propulsion - Ion thruster

- Feasibility evaluation of atmosphere-breathing ion thruster
  - RIT-10 tested on atmospheric gases (N$_2$, O$_2$, Xe)
  - 450 W nominal power
  - Thrust level of around 7 mN (~140 km)
  - Grid erosion not a crucial issue (after 500 h)

| RIT-10 | Xe | N$_2$ | 75% O$_2$
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<tr>
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<tr>
<td>Power (W)</td>
<td>467</td>
<td>574</td>
<td>540</td>
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<tr>
<td>MFR (mg/s)</td>
<td>0.489</td>
<td>0.194</td>
<td>0.170</td>
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<tr>
<td>$P_{prop}$ (mPa)</td>
<td>78.13</td>
<td>115.1</td>
<td>86.93</td>
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<tr>
<td>Thrust (mN)</td>
<td>14.71</td>
<td>6.83</td>
<td>6.79</td>
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<tr>
<td>$I_{sp}$ (s)</td>
<td>3100</td>
<td>3636</td>
<td>4328</td>
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</table>
Conclusions on ion thruster

- Operation basically feasible
  - Nitrogen and oxygen successfully yield thrust at a range of MFR
  - Thrust level sufficiently high to overcome drag force
  - Erosion not seen threatening to thruster lifetime

- However:
  - Power necessary to use low MFR exceeds on-board capabilities
  - Thrust density (thrust/surface area) too small; tested MFR are only feasible if propellant is stored during off-times
  - Propellant storage and compression to achieve usable pressure will increase system weight on satellite
Electrostatic propulsion - Hall thruster

- Proposed firstly by Busek Company in the early 2000s (US patent 6,834,492 B2)
- Proposal of Mars-based atmosphere-breathing system
  - Thrust/power of 30 mN/kW at 120 sccm of CO$_2$ mixture
  - 20 % of thrust efficiency
  - Inlet pressure of few 100 mPa
  - Martian atmosphere less studied
  - Planned maiden flight by 2025

All images: Courtesy of Busek
Electrostatic propulsion - Hall thruster

- PPS® 1350 (SPT) tested with atmospheric gases
  - $\text{N}_2$, $\text{N}_2/\text{O}_2$ + additive of xenon
  - Thrust of 20 mN at power input of 1 kW and MFR of 2.5 mg/s
  - Adding Xe increases thrust by 4-40 %
  - Wall erosion very severe
    - New materials required
    - Reconfiguration of magnetic field for shielding might reduce effects
Electrostatic propulsion - Hall thruster

• Computational studies
  – University of Toulouse, 2012
    • Target values: 20 mN, 1 kW, 10 % @ 250 km → 3 mg/s
    • Propellant storage necessary

    • High power (700-800 kW), high thrust (9 N) for an application below 100 km (VVLEO)
Conclusions Hall thruster

• Operation basically feasible
  – Usage of nitrogen, oxygen, air mixture, CO$_2$-based mixture
  – Higher thrust density yields smaller drag to be compensated
  – Measures to reduce wall erosion exist

• However:
  – Minimum MFR for operation high compared to collectable inflow
  – On-board propellant storage necessary
  – “The Hall-effect thruster application to compensate the atmospheric drag force for a spacecraft in a low orbit altitude is not possible because a large amount of propellant must be stored to compensate for the continuous force acting on the spacecraft for a long time, which increases the weight of the spacecraft and mission requirements.” (UToulouse, 2012)
Electromagnetic - Pulsed plasma thruster (PPT)

- Short-time pulsed electrical arc discharge
  - Across a solid or non-volatile liquid propellant surface (ablative PPT)
  - Or: through an injected liquid or gaseous propellant

- Usable at very low power inputs (few watts) and very low propellant masses per shot (few µg)
Electromagnetic - Pulsed plasma thruster (PPT)

- PPT never explicitly evaluated on air-like propellants
- Gas-fed PPT research started as early as the 1960s, e.g. at General Dynamics, General Electric
  - Usage of N\textsubscript{2}, Xe, H\textsubscript{2}
  - High propellant utilization efficiency of 60 % for N\textsubscript{2}
  - Thrust/Power ratio around 10-20 mN/kW
  - High discharge energies of 50-100 J

- 540 J-GPPT at Republic Aviation (later: Fairchild Industries), 1960s
  - Successful ignition with 10\textsuperscript{20} m\textsuperscript{-3} (from simulation at inlet: 10\textsuperscript{18} m\textsuperscript{-3})
Electromagnetic - Pulsed plasma thruster (PPT)

- **1990s/2000s Princeton University**
  - Low energy at high frequency (up to several kHz)
  - 6 mN/kW with argon
Electromagnetic - Air-breathing PPT

• Performance estimation – what to expect
  – For a typical ratio of 5 J of discharge energy per µg of injected mass
  
    \[ I_{sp} = 5000 \text{ s} \]
    \[ T/P = 15-20 \text{ mN/kW} \]
    (unoptimized; 1960s)
    \[ \approx 30 \text{ mN/kW} \] (optimized)
  – Discharge frequency variable

\[ h \rightarrow \text{Drag} = f(h) \]
\[ T/P \]
\[ f \]
\[ 5 \text{ J/µg} \]
\[ f \]
\[ m_{bit} \]

Worldwide data

Specific impulse \( I_{sp} \), s

Specific bank energy \( E_0/m_{bit}, \text{J/µg} \)

- PTFE
- Water
- DME
- Argon
- Xenon
- Nitrogen

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Air-breathing PPT – exemplary mission

- Exemplary mission scenario 1
  - FULL drag compensation for a small satellite (0.3 m²)
  - Then: Optimum discharge frequency depends on altitude
  - Still requires storage of propellant, thus full compensation might be difficult

![Diagram showing pulse energy and mass bit per pulse vs. altitude]

Mean solar activity; $C_D = 2.2$
Air-breathing PPT – exemplary mission

- Exemplary mission scenario 2
  - PARTIAL drag compensation resulting in a slowed-down orbit decay
  - As altitude decreases, PPT discharge frequency can be adjusted to keep energy and mass bit constant (thus: constant single-pulse performance)

\[ \text{Altitude } h, \text{ km} \]
\[ \text{Discharge frequency } f, \text{ Hz} \]

\[
\begin{align*}
\text{Power and required mass flux} & \quad \text{increase rapidly} \\
\text{At least } 4 \text{ kHz operation} & \quad \text{shown feasible} \\
\text{Starting point} &
\end{align*}
\]
Conclusions electromagnetic propulsion

• Operation theoretically feasible
  – Preliminary tests with gaseous propellants show high potential, but tests with atmospheric gases still missing
  – Thrust/power ratio in similar magnitude as electrostatic propulsion
  – Operation at low energy and mass inputs reduces need for on-board propellant storage

• However:
  – Electrode erosion phenomena unclear
Comparison of breathing electric propulsion systems

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Electrothermal</th>
<th>Ion thruster</th>
<th>Hall thruster</th>
<th>PPT</th>
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<tbody>
<tr>
<td>Operation with atmospheric gases</td>
<td>Partially tested</td>
<td>Feasible</td>
<td>Feasible</td>
<td>Partially tested</td>
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<td>Operation at low MFR</td>
<td>Not feasible</td>
<td>At high power</td>
<td>Not feasible</td>
<td>Feasible</td>
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<tr>
<td>Necessary exhaust velocity</td>
<td>Not feasible</td>
<td>Feasible</td>
<td>Feasible</td>
<td>Likely feasible</td>
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<td>Thrust/power</td>
<td>Sufficiently high</td>
<td>Sufficiently high</td>
<td>Sufficiently high</td>
<td>Sufficiently high</td>
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<tr>
<td>Thrust density</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
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<tr>
<td>Erosion</td>
<td>Severe</td>
<td>Low</td>
<td>Still severe</td>
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<td>Propellant storage</td>
<td>Very necessary</td>
<td>Very necessary</td>
<td>Very necessary</td>
<td>Necessary</td>
</tr>
</tbody>
</table>
Advanced concept - Inductively coupled plasma

- IPG 6\textsuperscript{th} generation at U Stuttgart
  - Mass flow rates of 20 to 400 mg/s (air, CO\textsubscript{2})
  - Current PG power: 15-20 kW with 22 %

- Electrode-less design implies no erosion, thus, suitable for all compositions of atmospheric gases
Advanced concept - ICP thruster

• ICP propulsion system design criteria
  – 4.4 mN per 1 mg/s for 10 MJ/kg (estimation from PG data)
  – As PG, same overall efficiency for continuous operation and pulsed operation of 1-10 ms
  – No optimization yet for propulsion purposes, but high potential
  – Scaling for lower power and reduced mass flow rates necessary

• Extension in future to propulsion system includes application of nozzle technology (mechanical, magnetic)