Feasibility study and comparative study of air breathing electric propulsion systems operating in very low Earth orbit conditions

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Air Breathing Electric Propulsion (ABEP) systems offer a promising solution to extending the lifetime of Very Low Earth Orbit (VLEO) missions by using residual atmospheric particles as a propellant. ABEP systems need to provide sufficient thrust to compensate for substantial aerodynamic drag present in VLEO environments. The feasibility of operating a hypothetical ABEP system of a given geometry at a given altitude is assessed via Direct Simulation Monte Carlo (DSMC) based on the following parameters: the mean pressure in the ionization chamber, compression factor and drag force acting upon the surface of the given geometry. Atmospheric models were used for reference to ensure realistic VLEO-like conditions. The comparative study is performed using a Global Plasma Model (GPM). A GPM can calculate the volume-averaged quantities of plasma systems with complex physics and reaction kinetics. The results of GPM are compared with a breadboard model of an Electron Cyclotron Resonance (ECR) ABEP system constructed by the Czech aerospace research institute (VZLU a.s.).

Very Low Earth Orbit (VLEO), Direct Simulation Monte Carlo (DSMC), Air Breathing Electric Propulsion (ABEP), Intake, Global Plasma Model (GPM)

I. INTRODUCTION

Carrying out missions in Very Low Earth Orbit (VLEO, orbits with mean altitude below 450 km) has several benefits over the standard operations in higher altitudes. However, atmospheric conditions at VLEO present challenges to the spacecraft (S/C) in the form of thermospheric winds, unpredictable solar activity and predominantly a substantial aerodynamic drag which must be compensated by a propulsion system to maintain the orbit and to reach desirable mission lifetimes. Air Breathing Electric Propulsion (ABEP) systems present a theoretical solution by using residual atmospheric particles as a propellant, however, neither of the concepts was, to date, demonstrated to work in orbit. A general schematic of a platform fitted with ABEP system presented in the Fig. 1 is described as follows:

Fig. 1. Schematic of a platform with ABEP system [1].

An intake is a device capable of collecting atmospheric particles, compressing them, and driving them into the thruster. Intakes vary in geometry and size, but all concepts share a common end goal: to scatter the atmospheric particles into the accelerator, which contains an ionization chamber capable of ionizing the compressed gas and accelerating it to generate thrust. The energy required for plasma ignition is meant to be supplied from solar arrays, attached to the S/C.

Current state of the art ABEP concepts feature RAMjet Electric Propulsion (RAM-EP) designed by SITAEL which was the first time worldwide experimentally validated system using an on-ground VLEO representative environment. They registered a successful ignition but were unable to compensate the atmospheric drag [2]. The Institut für Raumfahrtsysteme (IRS) in Germany provided an ABEP concept utilizing RF helicon-based Inductive Plasma Thruster (IPT). In early 2021 the IRS managed to achieve a successful ignition with satisfying preliminary results [3]. Other noteworthy concept originates in Japan Aerospace Exploration Agency (JAXA) employing Air Breathing Ion Engine (ABIE) with Electron Cyclotron Resonance (ECR). This system did not undergo any experimental verification but a study from 2012 confirmed the possibility of plasma ignition inside the ECR in 200 km of altitude [4]. Additionally in 2012, a different approach to ABEP was presented by BUSEK, focusing on the application of ABEP in extra-terrestrial atmospheres, mainly on Mars [5].

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studies show that the geometry and material of an intake contribute significantly to the results. Both University of Stuttgart [6] and the University of Colorado [7] carried out examinations of a parabolic intake made of specular reflecting material and concluded that it is significantly more efficient than material with diffuse reflection. Furthermore, the geometry of front-fitted parallel grid ducts is also under investigation. SITAEI features a split-ring configuration in their concepts. Meanwhile College of Aerospace Science and Engineering [8] compared the split-ring configuration with a honeycomb configuration and concluded that the latter configuration is more suitable for better intake performance. Therefore, in our own investigation of gas compression, we pick the two of the most prevalent geometrical configurations which appeared in recent years.

This article concerns the feasibility of ABEP systems by comparing an experimental setup with simulated data. Our goal is to determine whether plasma in the experimental model ignites at low pressures which are comparable to VLEO environment. This process is captured in the following chapter. The possibility of plasma ignition gives rise to the chapter called gas compression study, in which we examine whether such pressures can be obtained using our representative intake geometries. The conclusion features discussion regarding the results and possible future directions of the project.

II. PLASMA IGNITION STUDY

As the atmospheric pressure at VLEO is low, it is necessary to turn to plasma sources which can operate in such an environment. One of the viable sources is the ECR plasma source, which is used in the experimental breadboard model constructed by VZLU a.s. ECR is believed to compliment low operational pressures found at VLEO as the prevalent method of energy transfer happens between electrons and the high frequency electrodes. Electrons in the discharge chamber follow helical trajectories under the influence of the external magnetic field from coils. The resonance (i.e. maximum power transfer) occurs when the electron cyclotron frequency arising from their circular motion matches the frequency of the electric field created by the high frequency electrodes.

Schematics of the laboratory model of ABEP thruster seen in the Fig. 2 features a glass tube, a triad of extraction grids and the ECR plasma source. Experimental results were validated against Global Plasma Model (GPM) results using the kinetic system of N2/O2 mixture. We are using results from previously developed GPM of magnetized high frequency plasma source. The following paragraph succinctly describes the model as the full details can be found in [1].

At the crux of the GPM lies a set of balance equations, which are solved for all species except electrons (assuming quasi-neutrality) and for energy. Theses balance equations involve source terms which determine the temporal change in the key variable. The specie density changes via different mechanisms such as kinetic reactions, inflow, outflow, wall loss and wall gain. The energy balance of electrons and neutral gas particles involve different loss or gain channels. In electron energy equation, energy is introduced to the plasma through oscillating RF electric field and is, at first, transferred only to electrons. Different source terms of the energy balance equation describe the process of energy dissipation into the system. For a successful computation, the Electron Energy Distribution Function (EEDF) must be known. In ECR plasma, the EEDF is not Maxwellian and can be obtained for example through Boltzmann equation solver BOLSIG+ [9]. Thus, we can obtain electron temperature, whereas neutral gas energy equation allows us to obtain temperature of heavy particles. The GPM can be understood as a 0D model since it outputs only volume-averaged quantities. However, this is balanced out by low computational times so it can serve as a fast and efficient tool for estimating plasma properties and observing relationships among key variables.

As was stated above, GPM is based on a reaction kinetics. For example, the model used in this paper contains more than 600 unique reactions and processes. The input of GPM consists of species composition and initial conditions and parameters such as initial density of all species, initial pressure, energy from source and volume of the ionization chamber. The output of interest is plasma density from which we determine whether the plasma ignition occurs. As can be seen in [1], the GPM exhibits good accordance with the experimental data provided by VZLU a.s. This is best showcased in the Fig. 3 in which we can see the validation of GPM against the experiment.

Fig. 2. A schematic picture of the laboratory model of the ABEP thruster [1].

Fig. 3. Experimental validation of GPM: Two blue curves represent two independent measurements; orange curve is a result of GPM simulation [1].
The GPM in conjunction with experimental data also predicts that the plasma in ECR with reasonable dimensions would ignite only above 5 mPa. With such information in mind, we conducted a gas compression study in order to pinpoint if such pressures are achievable at VLEO altitudes.

III. GASE COMPRESSION STUDY

Most of the theoretical results of the performance of any ABEP systems mentioned in the introduction section were gathered solely via simulations. Similarly, our investigation of ABEP intake systems was conducted using primarily Direct Simulation Monte Carlo (DSMC) method as DSMC corresponds well with the molecular flow regime of particles expected to be found at the intake of the S/C. Our DSMC cases were conducted with dsmcFoam+, a solver which is a part of the OpenFOAM open-source software. The DSMC solver requires precise information about the simulated environment, which is imposed at the model’s boundary condition. As the atmosphere in VLEO changes based on a variety of different parameters, an atmospheric empirical model with the ability to provide reliable data must be employed. We utilize the NRLMSISE-00 model which is considered a staple model in space research and simulation [10]. NRLMSISE-00 is used primarily to determine number densities of dominant species in VLEO. Additional benefit of NRLMSISE-00 is its ability to provide information regarding density of highly reactive oxygen generated by photochemical dissociation of ozone molecules. This reactive oxygen proves to be a non-negligible factor while considering the lifespan of ABEP components, as it has high corrosive effect especially contributing detrimentally to extraction grids. A representative graph of number densities of species in VLEO can be seen in the following Fig. 4:

By employing DSMC method we were able to compute not only atmospheric drag $F_D$ affecting the outer walls of the S/C but also mean pressure $p_{\text{mean}}$ in the ionization region. We chose two different geometries, as seen in Fig. 5. As stated in the introduction, we decided on popular intake shapes. Firstly, an S/C consisting of a parabolic shaped intake leading directly to the ionization chamber with a 90% reflecting grid fitted at the end was envisioned. The second geometry is more complex in design, consisting of a split-ring intake, not unlike in concepts of SITAEL, and cone shaped compartment leading to the ionization chamber that is also fitted with a grid with the same reflection coefficient. Both ionization chambers were modelled with the experimental breadboard model in mind to share comparable dimensions.

![Fig. 5. General parabolic and split-ring configuration.](image)

The first set of simulations determine at which altitude the selected geometry performs the best. The simulations are performed at five different altitudes between 150 km and 250 km for both geometries.

![Fig. 6. Total gas pressure per cell – parabolic configuration at 150 km altitude.](image)

Fig. 6 shows a total gas pressure inside and outside of the S/C. The parameters of interest are $F_D$, $p_{\text{mean}}$, the ratio between the two and lastly, a compression factor $\beta$ representing the ratio between mean pressure in the ionization chamber and the pressure outside of the S/C. Considering all these parameters, we can determine the optimal altitude to be at 175 km. Although we barely reach the desirable 5 mPa at this altitude, the drag force remains optimal. Furthermore, both parameters can be further improved by changing the geometry of the S/C or by employing front-fitted ducts or by using different materials. The following Tab. 1 shows the best results for both geometries:

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$p_{\text{mean}}$ [mPa]</th>
<th>$F_D$ [mN]</th>
<th>$\frac{p_{\text{mean}}}{F_D}$ [m$^{-2}$]</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parabolic</td>
<td>5.719</td>
<td>0.808</td>
<td>7.078</td>
<td>55.77</td>
</tr>
<tr>
<td>Split-ring</td>
<td>4.588</td>
<td>1.031</td>
<td>4.450</td>
<td>44.75</td>
</tr>
</tbody>
</table>

![Table I. Comparison of both geometries at 175 km of altitude](table)

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The second set of simulations is performed at the optimal altitude by scaling key elements or changing the number of elements in both geometries. The parabolic configuration allows for scalable parabolic intake as well as scalable ionization chamber. The split-ring configuration features variable parameters capable of altering the number of lamellas per ring or the number of rings as well as scalable intake length. For example, the split-ring configuration performed better with shorter intakes, as seen in the following Tab. 2.

TABLE II. PERFORMANCE PARAMETERS FOR DIFFERENT LENGTHS OF SPLIT-RING CONFIGURATIONS

<table>
<thead>
<tr>
<th>x [cm]</th>
<th>15</th>
<th>22.5</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{\text{mean}}$ [mPa]</td>
<td>5.390</td>
<td>5.084</td>
<td>4.588</td>
</tr>
<tr>
<td>$F_C$ [mN]</td>
<td>0.972</td>
<td>1.059</td>
<td>1.031</td>
</tr>
<tr>
<td>$\tau_{\text{mean}}$ [m$^{-2}$]</td>
<td>5.545</td>
<td>4.801</td>
<td>4.450</td>
</tr>
<tr>
<td>$\beta$</td>
<td>52.56</td>
<td>49.58</td>
<td>44.75</td>
</tr>
</tbody>
</table>

As far as the parabolic configuration is concerned, the geometrical variations reveal that our base geometry performs the best. This is the one pictured in the Fig. 5. The results are further discussed in the conclusion section.

IV. CONCLUSION AND FUTURE WORK

A. Plasma Ignition Study

Studies involving GPM provided us with an important value below which plasma ignition is no longer achievable. In conjunction with experiment carried out by VZLU a.s. we concluded that 5 mPa is the lowest pressure at which plasma can be ignited in the breadboard model’s ionization chamber.

The GPM method is a swift tool capable of offering good estimates of plasma properties. This evokes the idea of coupling the DSMC method with GPM. Implementing such conjunction of both methods would allow us to accurately compute the drag force, calculated using DSCM method, as well as the thrust, calculated by GPM (based on pressure and gas composition from DSMC). Deciding whether the thrust is net positive by directly comparing the two variables should lead to better understanding of the feasibility of the ABEP concept.

B. Gas Compression Study

Through DSMC, a study of performance parameters such as mean pressure in the ionization chamber, drag force acting on the surface of the spacecraft or compression factor at various altitudes was performed. Based on the mean pressure and the ratio between the mean pressure and the drag force, we determined that the optimal altitude at which further studies would be conducted is 175 km. Both mean pressure and the drag force decreased with increasing altitude, which was to be expected. The mean pressure to drag force ratio at this altitude yielded the most favorable results: the mean pressure was high enough for the ignition of plasma in the ionization chamber to still be theoretically possible. Once the optimal altitude was selected, a series of geometrical studies was performed to determine the optimal geometry in terms of best performance parameters. Concerning the parabolic intake, we simulated a geometry with parabolic intakes of various lengths. The results suggested a better performance for longer intakes. Reducing the overall length of the split-ring intake to be comparable with the parabolic configuration, led to better performance as well. Subsequently, we picked the geometrical variations that performed best for both geometries and compared them. Surprisingly, both optimal geometries performed similarly, nevertheless the parabolic configuration showed slightly better compression factor and was less affected by the atmospheric drag.

C. Future Work

Apart from further improvements to the experimental device, our current research gravitates towards the coupling of the DSMC method and GPM, as was stated prior. Additional plans include more in-depth look into the effects of atomic oxygen on the S/C. More specifically, the ABEP systems are usually imagined to be fitted with accelerating grids which pose an unstable element in their implementation. The abundance of highly reactive atomic oxygen proves detrimental to many ABEP electrical components, including the grids. Thus, comprehensive research including experimental data of the grid lifetime is currently in preparation.

Lastly, a more detailed insight into plasma processes and composition is required as the GPM cannot solely comprehend all underlying phenomena. The optical emission spectroscopy arises as a suitable candidate for additional plasma diagnostics which can, as well, be used to validate the GPM results.

ACKNOWLEDGMENT

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REFERENCES


