MAFLNOHYDRODYNAMIC ENERGY BYPASS APPLICATIONS FOR SINGLE STAGE-TO-ORBIT VEHICLES

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Extended Abstract
The global political structure has changed dramatically since the breakup of the former Soviet Union. World changes have caused the U.S. to reprioritize its national hypersonic needs. The United States government has looked the need of the future, and hypersonic aerospace plane is one of the systems included in alternative force structures. One of the hypersonic aerospace plane concepts would involve magnetohydrodynamic (MHD) technology, or the AJAX hypersonic flight vehicle concept, originally proposed by Russian scientist Vladimir Froissadt.

This paper is to report the current progress and findings of an air-breathing horizontal take-off and landing design concept using an MHD energy bypass injector ramjet engine being studied at MSE Technology Applications Inc. (MSE-TA) and HyperTech Concepts for NASA Langley Research Center under Phase II NASA Small Business Innovative Research (SBIR). Modified NASA Ames MHD code with new Scramjet model and other tools were used to examine the total system performance. Fuel Reforming, Non-equilibrium ionization, and design integration were also investigated. Both cruiser and space launch propulsion configurations have been investigated. The overall operational concept was examined to determine the overall cost-effectiveness.

Introduction
The purpose of this paper is to report a project which studies an air-breathing horizontal takeoff and landing design concept using a magnetohydrodynamic (MHD) energy bypass injector ramjet engine. Both cruiser and space launch propulsion configurations were investigated. The baseline configuration is a blended wing-body design. The overall technical objective of paper is to provide an up to date system study to demonstrate the feasibility of MHD energy bypass application in single-stage-to-orbit (SSTO) and cruise vehicles. The specific objectives of the study being reported by this paper are enumerated as follows: 1) Use a nonequilibrium model to calculate nonequilibrium engine ionization conditions and magnetic field strength; 2) Provide a brief hydrocarbon fuel reforming study including inlet fuel injection effect; 3) Magnet size and weight requirement, and 4) Perform a vehicle sizing study.

Some of the preliminary results are reported in this extended abstract. The full report will give the better description and results.

Hypperonic Inlet Fuel Injection
A control-volume approach to estimating the effect of fuel injection on the compression efficiency of the inlet has been conducted. The results of these calculations on a four shock 2-D inlet are presented below showing how the location of fuel injection affects inlet performance versus fuel injection location and compared to the case with no inlet fuel injection.

The classical temperature-entropy diagram for the air-based scramjet cycle is shown in Figure 1 with cycle stations numbered in accordance with conventional practice. In this representation, free-stream air at Station 0 is compressed in the inlet to Station 2 then further compressed in the inlet isolator to the conditions of Station 3. Heat is then added to the air stream to achieve the combustor exit conditions at Station 4, which is then expanded through the exhaust nozzle to the freestream ambient pressure at Station 10. Component efficiencies can be expressed in different ways in this scheme. For example the inlet compression efficiency can be defined in terms of the work that would be required to compress the flow to the same pressure by an isentropic process versus the work required for the actual process – for example the isentropic process from point 0 to point 2s versus the
actual process from point 0 to point 2. Another way to express performance is to expand the flow isentropically from the actual process point back to a baseline pressure, for example from point 2 to point X2. Both of these approaches have shortcomings in terms of defining a meaningful process path when the working fluid can be a two-phase mixture. The second approach, isentropic expansion from point 2, was used previously to estimate the compression efficiencies associated with fuel injection at different points in the inlet. The effect of fuel condensation upon expansion to ambient pressure was artificially suppressed and the fuel/air mixture was treated as always being in the vapor phase. A more accurate comparison of inlet performance with fuel injection can be had by comparing the static temperature, entropy, velocity, and Mach number existing at point 2 for the different fuel injection locations.

Figure 2. Four-shock mixed-compression inlet

Figure 2 shows the inlet geometry assumed in this analysis of fuel injection in the inlet of a hypersonic vehicle. A control volume was drawn around the geometry of each attached oblique shock wave to apply the integral forms of the equations for the conservation of mass, energy, and momentum. Fuel injection was assumed to proceed with perfect mixing of the fuel and air achieved across the entire control volume. The fuel was assumed to be liquid n-heptane at 530 R and 1000 psia and at the overall stoichiometric fuel/air mass ratio (f/a = 0.06588 for n-heptane). Injection parallel to the flow was assumed in order to minimize the irreversibilities of mixing. This control-volume approach also yields the classic oblique shock relations in the absence of fuel injection.

The pressure ratio across the first three shocks was held constant for this series of calculations since equal shock pressure ratios generally result in the lowest overall entropy generation and the highest inlet total pressure recovery. The pressure ratio of the last shock was then chosen to divert the inlet flow back to the pure axial direction to minimize the overall vehicle drag. The static pressure at the entrance of the inlet isolator was also held constant at 9.298 psia for all cases, which was the value of P2 obtained for the case of no inlet fuel injection, as shown in Figure 2. While still an idealization, these assumptions allowed us to capture the main effects of fuel injection from different locations on the pressures, temperatures, and residence times of the fluid in the inlet.

The compression efficiency was calculated from the enthalpies of the separate freestream air and fuel supply conditions (cycle station 0), the calculated conditions at the entrance to the inlet isolator (cycle station 2), and the endpoint of an isentropic blowdown from cycle station 2 to ambient pressure (cycle station 2x), assuming no condensation of the fuel:

$$\eta_{comp} = \frac{h_{2x} - h_{2}}{h_{2} - h_{0}}$$

The values of \(\eta_{comp}\) obtained from this analysis are shown in Table 1, as reported previously. In addition, the values of the mixed stream Mach number, velocity, static pressure, static temperature, and molar entropy are also reported in Table 1. These results indicate that the injection of fuel into the high velocity air flow on the forebody of the vehicle produces a significantly higher final mixture entropy and static temperature with lower Mach number and velocity than injection of the same fuel flow further downstream into slower-moving air. The static temperatures obtained at the isolator entrance also indicate that no cracking of the fuel can be expected upstream of this point, limiting the cooling effect of the fuel injection to vaporization and sensible heating with no benefit from endothermic cracking. These additional results confirm that there is a significant
overall performance penalty associated with injecting the fuel into the high velocity inlet air flow as opposed to the slower flow within the combustor. A full description of the control-volume inlet analysis method will be enclosed in next month's report.

**Magnet Design Consideration**

Investigations are ongoing with experts in this area to further gain understanding of the magnet designs. Based on the system analysis, a magnet with the following design is being considered. Quote from American Madgetics Inc. is enclosed as follows:

- Room temperature bore, with access.
- Horizontal configuration, 24-inch diameter, 6-ft length.
- Homogeneity would be “as-wound” (this can be improved for additional cost).
- 3 Tesla (rating, although could be pushed to 4T).
- Active shielding was not recommended (adds 500 lb), since 3T field drops off substantially outside dewar
- Magnet weight would be approx. 1200 lb, plus cryostat weight of 800 lb, for a total of approximately 2000 lb
- Cost of superconducting magnets is generally about $100K per Tesla -- this magnet would cost approx. $400K.
- The finished OD of the package, which would be the OD of the cryostat, is about 4 feet

**Preliminary System Study**

One-dimensional code and Builder’s approach were used to re-examine the system. The results are as follows:

With the Builder’s Second Law Brayton cycle solution, and estimated mass flow rate in the flowpath, following figures are generated: Figure 3 shows the airflow variations for the different flight speed and figure 4 shows module mass flow variations under different Flight Speed. Figure 5 to 9 demonstrate the influence of MHD implementation to the hypersonic vehicles. We believe the sensitivity of MHD augmentation is crucial to the vehicle design, and will be discussed further during the conference.

**Summary**

Primary system study, individual technology verification, and overall operation and mission analysis have been successfully accomplished. An enhanced MHD code from NASA-AMES was acquired and modified to carry out the inlet ramp calculation, ionization (from seed to nonequilibrium) section, and scramjet calculation. Ionization required to achieve necessary energy bypass and individual nonequilibrium ionization methods were investigated. A hydrocarbon fuel reforming study was performed, and some exciting results were discovered. Simple operation and mission analysis were also performed.
Figure 3. Airflow variations vs. Flight Speed

Figure 4. Module Mass Flow variations vs. Flight Speed
Figure 5. By-pass Parameters vs. different loading factors

Figure 6. By-pass energy per module vs. flight speed
Figure 7. MHD influence to ISP for the vehicles

Figure 8. MHD influence to ISPE for the vehicles
Figure 9. ISPE vs. Flight Speed for different vehicles

<table>
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<th>Fuel Injection Location</th>
<th>$\eta_{\text{comp}}$</th>
<th>$M_2$</th>
<th>$u_2$ (ft/s)</th>
<th>$P_2$ (psia)</th>
<th>$T_2$ (R)</th>
<th>$S_2$ (Btu/lb-mol)</th>
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<td>0.7969</td>
<td>2.658</td>
<td>4463</td>
<td>9.298</td>
<td>1331</td>
<td>56.920</td>
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<td>0.8217</td>
<td>2.807</td>
<td>4585</td>
<td>9.298</td>
<td>1255</td>
<td>56.402</td>
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<td>9.298</td>
<td>1196</td>
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<td>9.298</td>
<td>1178</td>
<td>55.855</td>
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Table 1. Calculated compression efficiencies and inlet isolator entrance conditions for the four-shock inlet.