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# MAGNETOGASDYNAMIC POWER EXTRACTION AND FLOW CONDITIONING FOR A GAS TURBINE[1]

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## Abstract

An extension of the Russian **AJAX** concept to a turbojet is being explored. This magnetohydrodynamic (MHD) energy bypass engine cycle incorporating conventional gas turbine technology has MHD flow conditioning at the inlet to electromagnetically extract part of the inlet air kinetic energy. The electrical power generated can be used for various on-board vehicle requirements including plasma flow control around the vehicle or it may be used for augmenting the expanding flow in the high speed nozzle by MHD forces to generate more thrust. In order to achieve this interaction, the air needs to be ionized by an external means even up to fairly high flight speeds, and the leading candidates may be classified as electrical discharge devices. The present kinetic modeling calculations suggest that the use of electron beams with characteristics close to the commercially available e-beam systems (electron energy –60 keV, beam current –0.2 mA/cm$^2$) to sustain ionization in intermediate pressure, low-temperature (P=0.1 atm, T=300 K) supersonic air flows allows considerable reduction of the flow kinetic energy (up to 10-20% in M=3 flows). The calculations also suggest that this can be achieved at a

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reasonable electron beam efficiency ($\eta$~5), even if the e-beam window losses are taken into account. At these conditions, the exit NO and **O** atom concentrations due to e-beam initiated chemical reactions do not exceed 30 ppm. Increasing the beam current up to **–2** mA/cm$^2$, which corresponds to a maximum electrical conductivity of $\sigma_{max}$~0.8 mho/m at the loading parameter of K=0.5, would result in a much greater reduction of the flow kinetic energy (up to 30-40%). The MHD channel efficiency at these conditions would be greatly reduced (to $\eta$~1) due to increased electron recombination losses in the channel. At these conditions, partial energy conversion from kinetic energy to heat would result in a significant total pressure loss ($P_0/P_{0i}$~0.3). The total pressure loss can be reduced operating at the loading parameter closer to unity, at the expense of the reduced electrical power output. Raising the beam current would also result in the increase of the exit **O** atom concentrations (up to 600 ppm) and NO (up to 150ppm).

## 1. Introduction

The Russian AJAX hypersonic vehicle concept has coupled magnetohydrodynamic (MHD) elements at the inlet and nozzle of a scramjet to increase its performance [1]. Analyses of the concept lead to the conclusion that energy bypass of a scramjet can result in subsonic ramjet propulsion being maintained in the Mach No. 10-16 speed range [2]. In order to explore the benefits of this technology, a design concept of a single stage-to-orbit **(SSTO)** vehicle was advanced which indicated an approximate 15% performance increase over an air-breathing rocket-based-combined-cycle ejector ram-scramjet reference design [3]. ***An*** examination of the feasibility of MHD energy bypass with turbojets has been proposed [4]. As with the scramjet, three primary aeropropulsion purposes are served by the concept. First, the enthalpy into the combustor is reduced allowing more efficient addition of energy in the combustor without exceeding temperature limitations on the turbine materials. Second, the applied electromagnetic fields and their body forces can enhance off-design performance by manipulating the flow features in supersonic/hypersonic inlets thereby reducing total pressure losses, and entropy changes for the same level of flow compression by other means. Third, electrical power removed can be used for various on-board vehicle requirements including plasma flow control around the vehicle. In addition, the expanding flow in the high speed nozzle may also be augmented by the electromagnetic forces to generate more thrust. **A** concept vehicle showing power generation and distribution is shown in Figure 1.

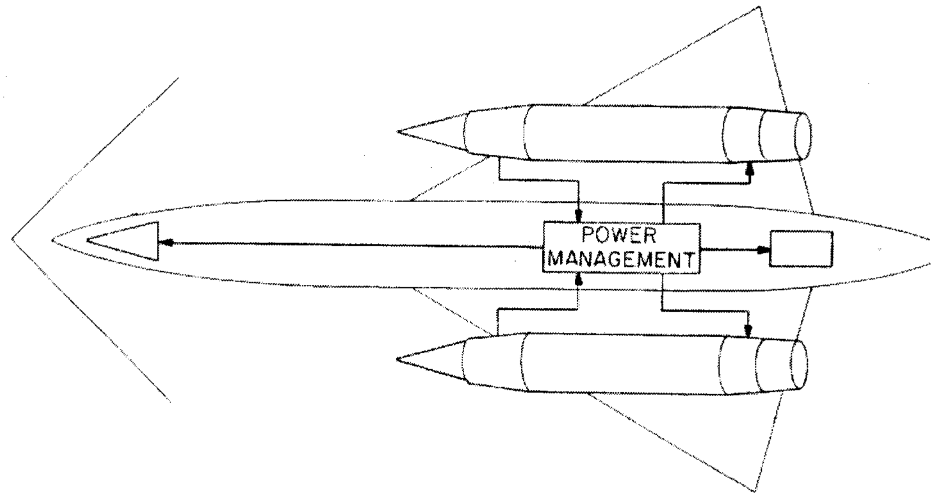


Figure 1. Concept vehicle showing MHD energy bypass of a turbojet and potential energy management system.

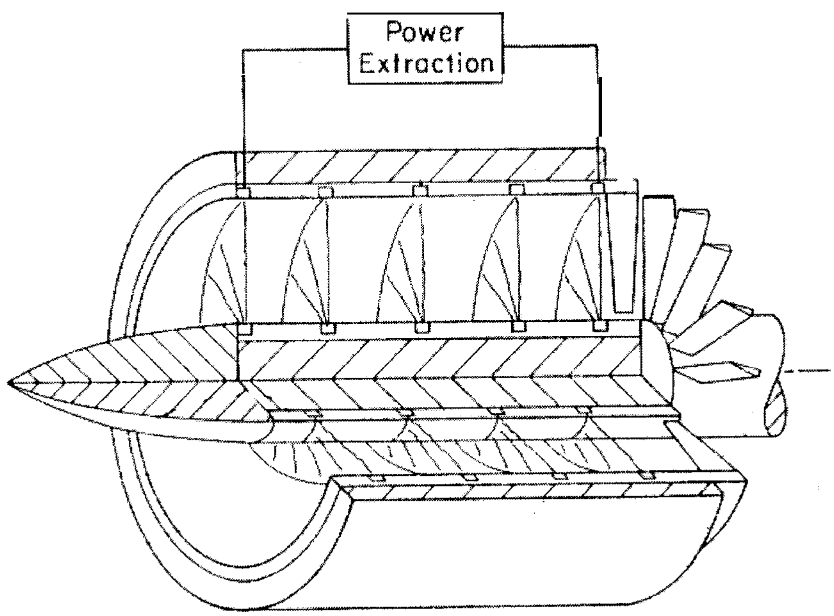


Figure 2. Annular Hall type MHD power extraction concept for the inlet of a turbojet showing spiral path of conductivity generated by e-beam ionization.

In order to be geometrically compatible with a turbojet the authors propose an annular Hall type generator concept shown in Figure 2. The proposed concept has a "spiral curtain" of conductivity shaped like an auger in the annular passage. The conductivity is generated by opposed electron beam guns as presented in Ref. [5] in order to provide uniform conductivity in the core flow outside of the boundary layer. This should prevent undesirable MHD interaction with the boundary layers. The concept potentially offers variable inlet geometry performance without the complexity of moving parts simply by varying the loading parameter. Another critical technology necessary for the implementation of this concept is lightweight cryogenic magnet technology. Recently, superconducting properties of carbon nanotubes have been measured [6] offering the possibility of lightweight cryogenic magnets for aerospace applications.

The objective of the present work is to study feasibility of the use of MHD power generation and flow deceleration in low-temperature, e-beam ionized nonequilibrium supersonic air flows, with the primary application being MHD diffuser for a turbojet engine. The main purpose of the present study is to determine whether ionization efficiently generated in a cold supersonic flow using a high-energy electron beam can be used to produce Lorentz force of a magnitude sufficient to generate substantial amounts of electrical power and to considerably reduce the kinetic energy of the flow.

## 2. Kinetic modeling calculations

The modeling calculations have been performed using the quasi-one-dimensional nonequilibrium MHD air flow code developed at OSU [7]. Briefly, the code incorporates master equation for state-specific vibrational populations of $N_2$ and $O_2$, Boltzmann equation for electrons, species concentration equations for neutral and ionized species (complete nonequilibrium air chemistry), one-dimensional gas dynamics equations, and generalized Ohm's law. The detailed description of the kinetic model used can be found in Ref. [7].

In the present paper, the calculations have been done for the constant cross section annular flow between two coaxial cylinders of 40 cm and 50 cm radius, and 100 cm long. Note that the one-dimensional approximation used in the present work is valid only if the annulus height is much smaller than the cylinder diameter. The inlet flow conditions are P=0.1 atm, T= 300 K, and M=3.0 (U=1100 m/s, mass flow rate $\dot{m}$=36.6 kg/sec). This approximately corresponds to the conditions downstream of a mild oblique shock (deflection angle $12^0$, wave angle $25^0$, free stream Mach number $M_{fs}$=3.8 at the 23 km altitude).

Ionization in the annulus is produced by a uniformly distributed high-energy electron beam. The stopping distance of a 20 keV electron beam (for the electron energy after the electron gun window) at the given inlet density and pressure is approximately **12** cm [7,8], which is consistent with the present annulus height. Raising the electron energy at the same annulus height and static pressure would increase the stopping distance and therefore result in wasting of a substantial fraction of the beam power. In the first series of calculations, the e-beam power loading is taken to be 1 eV/molecule/sec, which for a 20 keV beam energy corresponds to a reasonable beam current density of *0.2* mA/$cm^2$ [7]. For comparison, a Kimball Physics 80 keV e-beam (electron energy before the window) with current densities up to 1 mA/$cm^2$ has been extensively used for e-beam experiments at the Nonequilibrium Thermodynamics Group at **OSU** [9-13]. The window losses across the 25 $\mu$m aluminum foil window are estimated at approximately 40 keV [9]. The stopping distance of the resultant –40 keV beam is estimated to be –3 cm in 1 atm air (or –30 cm in 0.1 atm air). The length of the Kimball Physics electron gun is –0.5 m. This illustrates that the e-beam parameters used in the present calculations are consistent with the commercially available electron beam systems.

**A** uniform tangential magnetic field $B_\theta$=10 T is applied in the annulus, as shown in Fig. 3. (This is done for convenience of the calculation while the actual device is planned to have a radial magnetic field.) Both radial and axial electric field can be applied thereby controlling the radial (Faraday) current, $J_r$, and the axial (Hall) current, $J_z$ (see Fig. 3) [14]. In practice, this is achieved by using pairs of concentric ring electrodes, as shown in Fig. 3. The calculations have been done for both Faraday ($J_z$=0) and Hall electrode configurations ($E_r$=0) for different values of the loading parameter $K_{Faraday}=E_y/u_zB_r$ and $K_{Hall}=E_z/\beta u_zB_r$ (here $\beta$ is the Hall parameter). For the Faraday generator, K=l corresponds to the open circuit regime (electrodes are disconnected from the load), and K=O is the short circuit regime (opposing electrodes are shorted). For the Hall generator, K=l is also the open circuit regime and K=O is the short circuit regime.

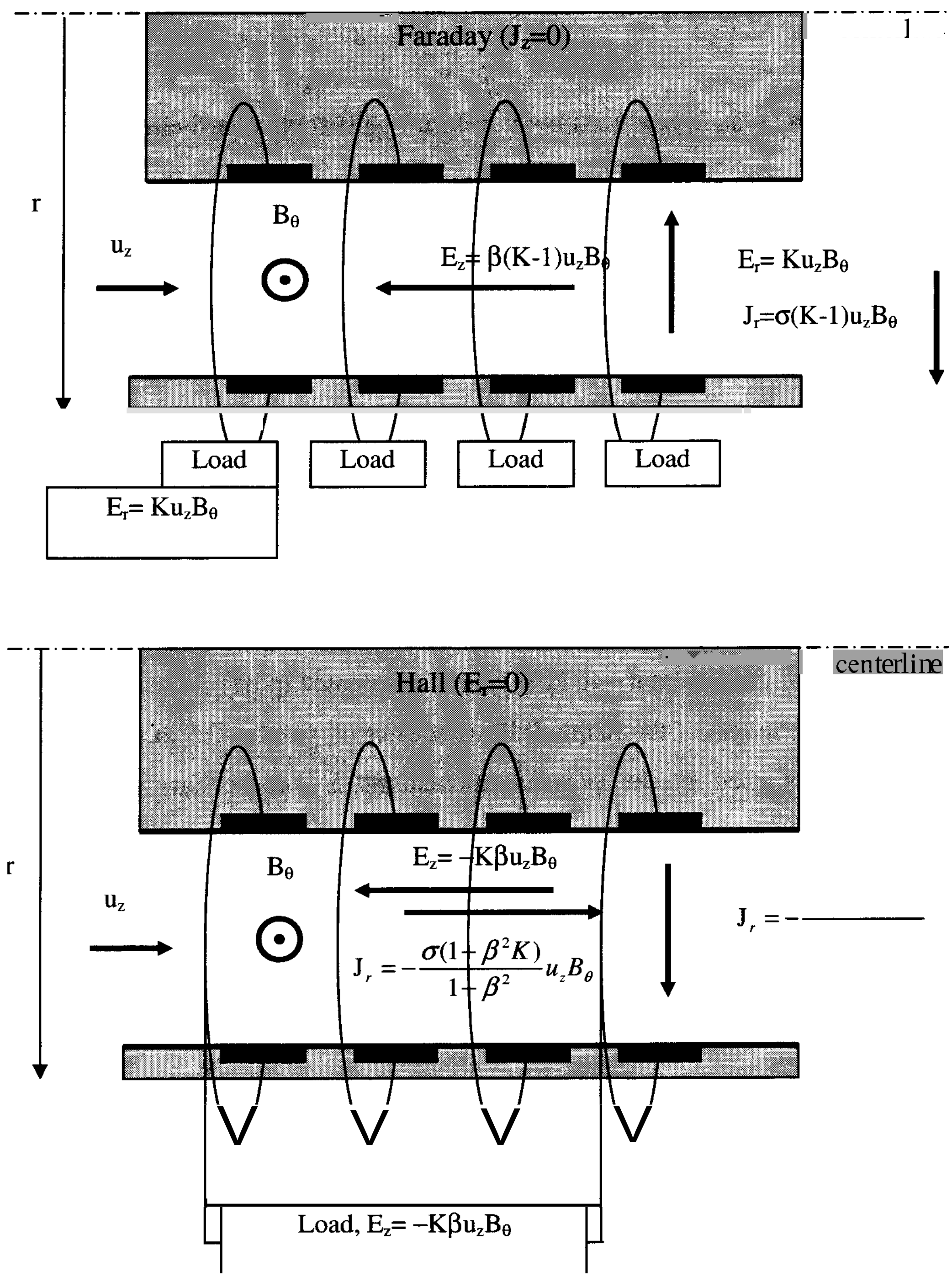


Figure **3.** Electrode configurations for the Faraday and Hall accelerators.

The results for different values of the loading parameter are summarized in Figs. **4-8.** First, it can be seen that for the given flow parameters and the e-beam power of 1 eV/molecule/sec, the efficiency $\eta$ of the MHD generator/decelerator, defined as the ratio of the extracted electric power to the absorbed e-beam power, can be rather high (see Fig. **4).** Indeed, at these conditions the e-beam power absorbed by the flow is approximately 110 kW. This should be compared with the extracted MHD electrical power (up to 1.5 MW at $K_{Faraday}=K_{Hall}=0.5$ and the efficiency of $\eta=15$) and the power converted from kinetic energy to heat (up to 5.0 MW at $K_{Faraday}=0$ and $K_{Hall}=1$). The difference between the kinetic energy reduction and the generated electrical power is the Joule heat added to the flow.

At these conditions, the static pressure at the channel exit increases by up to **20%** (at K=0.5) to **40%**($K_{Faraday}=0$ and $K_{Hall}=1$). The initial flow power (total enthalpy times mass flow rate) is **24.1** MW at the mass flow rate of ***m*** **=36.6** kg/sec. It should be noted, however, that the total e-beam power used will be higher due to the window losses (about **40** keV for a 25 µm thick aluminum window), which for the present geometry is equivalent to additional 220 kW power loss. This reduces the generator efficiency at K=0.5 to $\eta=5$. It can also be seen that by varying the loading parameter the MHD device can be used both as an electrical power generator ($K_{Faraday}=1-K_{Hall}=0.5$, electrical power output is maximum) and as a flow decelerator ($K_{Faraday}=1-K_{Hall}=0$, kinetic energy reduction is maximum). In the first case, approximately one half of the power extracted from the flow kinetic energy is converted into electrical power. In the second case, all extracted kinetic energy is converted into heat.

Figure 5 shows the dependence of the exit Mach number on the loading parameter. One can see that a M=3 air flow can be decelerated down to **M=2.6** at K=0.5 (power generator regime) or to **M=2.4** at $K_{Faraday}=0$, $K_{Hall}=1$ (flow decelerator regime). Note that in this case deceleration does not result in excessive flow heating. The maximum temperature increase at these conditions is only about 50 **K,** for the lowest exit Mach number.

Due to the large values of the Hall parameter in this low-density flow (**$\beta$=12-35** depending on the electron temperature, i.e. on the loading parameter), the transverse current, J„ greatly exceeds the axial current, J„ and the axial electric field, E„ greatly exceeds the transverse field, $E_r$, for both electrode configurations. Figures 6, 7 show maximum transverse current density and axial electric field in the MHD channel as functions of the loading parameter K. For the present channel geometry, the short-circuit transverse current density of 200 mA/cm$^2$ would correspond to the total current of about 5,000 A, and the open-circuit axial field of 1300 V/cm would correspond to 130 kV total voltage. These conditions correspond to the flow electrical conductivity of up to -0.4mho/m (see Fig. 8), which is considerably lower than the conductivity typically achieved in high-temperature MHD flows, up to a few tens of mho/m [15]. Although the axial field electric field is rather high, it is still more than an order of magnitude lower than the breakdown voltage. At these conditions, the reduced electric field E/N did not exceed $E/N=0.5\cdot10^{-16}$ V$\cdot$cm$^2$ (the breakdown voltage is $\sim10^{-15}$ V$\cdot$cm$^2$).

Note that at these high values of the Hall parameter ($\beta$>>1), the Hall generator characteristics are very close to the ones for the Faraday generator at $K_{Faraday}=1-K_{Hall}$ (see Figs. 4-8). Indeed, in this case the magnitudes of the Lorentz force for the two schemes are very close,

$$F_{z,\,Hall} = -\frac{\sigma(1+\beta^2 K_{Hall})}{1+\beta^2} u_z B_\theta^2 \cong \sigma(1-K_{Faraday}) u_z B_\theta^2 = F_{z,\,Faraday} \qquad (1)$$

The present calculations suggest that due to relatively modest electron beam power, e-beam initiated air chemistry processes, such as oxygen dissociation by electron impact and subsequent nitric oxide formation, are rather slow. Indeed, calculated exit O atom and nitric oxide fractions do not exceed 30 ppm. Also, since the reduced electric field E/N in the MHD channel is so low, vibrational excitation of nitrogen remains fairly weak, which also slows down the NO formation by Zel'dovich mechanism reactions.

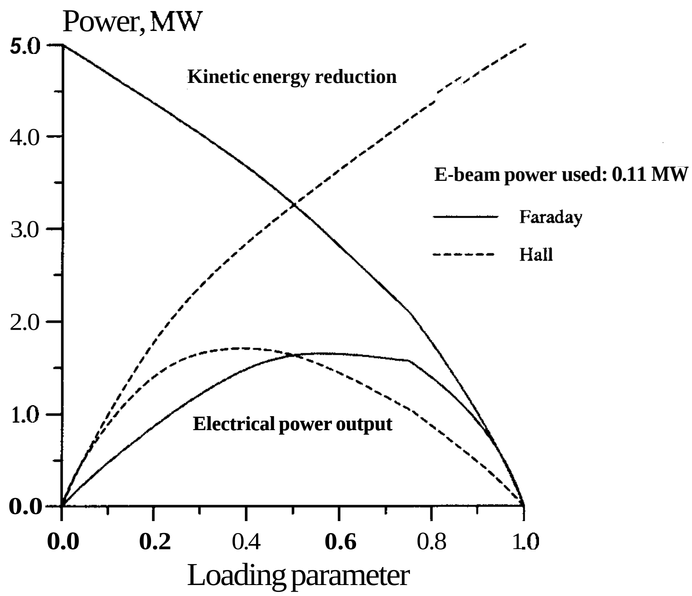


Figure 4. Extracted electrical power and kinetic energy reduction as functions of the loading parameter. E-beam load is 1 eV/molecule/sec

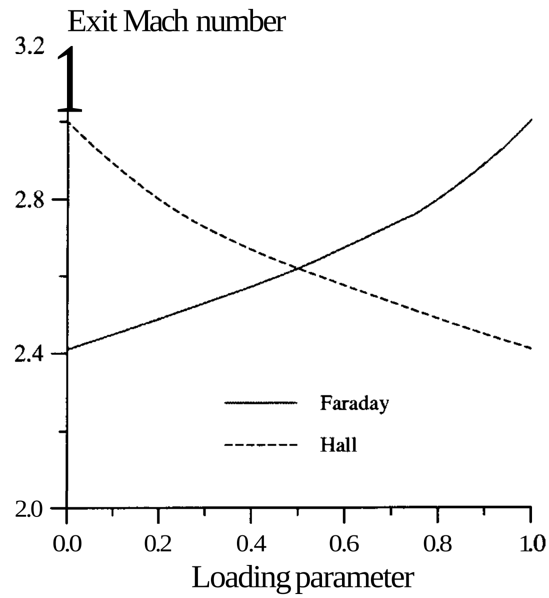


Figure 5. Exit Mach number as a function of the loading parameter. E-beam load is 1 eV/molecule/sec

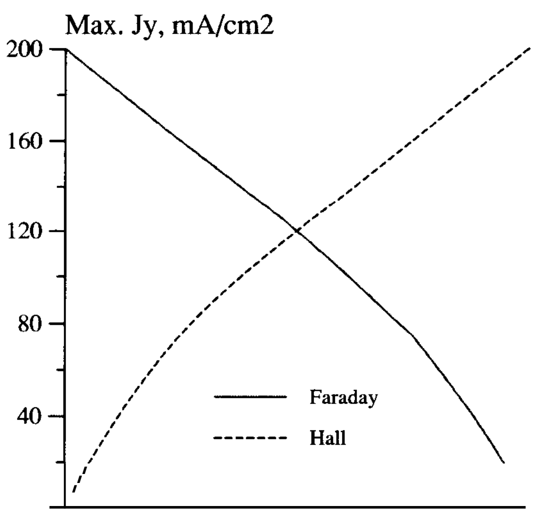


Figure 6. Maximum transverse current density as a function of the loading parameter. E-beam load is 1 eV/molecule/sec

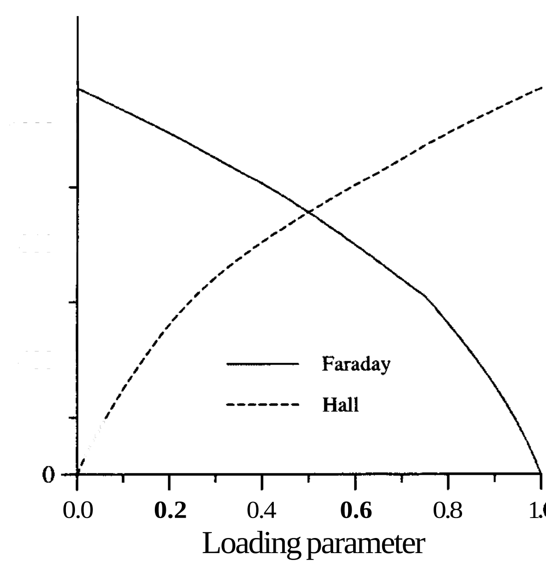


Figure 7. Maximum axial electric field as a function of the loading parameter. E-beam load is 1 eV/molecule/sec

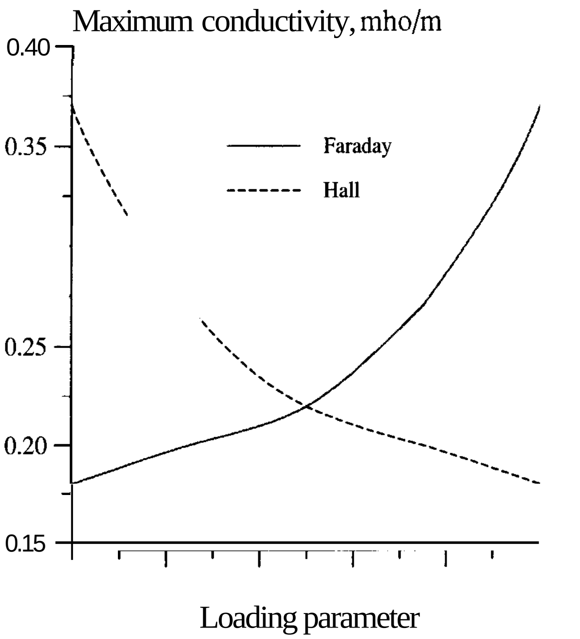


Figure **8.** Maximum electrical conductivity as a function of **the** loading parameter. E-beam load is **1** eV/molecule/sec

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From Fig. 9, it can be seen that increasing the e-beam power allows significant reduction of the exit Mach number, down to M=1.3 at the beam power of 1.4 MW. At these conditions, the static pressure along the channel increases by a factor of 3.5. However, at these conditions the generator efficiency is drastically reduced, down to $\eta$=3 (neglecting e-beam window losses, see Fig. 10) or q=l (with window losses). Figure 11 shows the dependence of the extracted electric power and the kinetic energy reduction on the absorbed e-beam power (without window losses). The main reason for the efficiency reduction at the high beam powers is the increase of the electron-ion recombination losses, which scale as a square of the electron density (or electric conductivity). The calculations suggest that electrical power generated in the MHD diffuser should be sufficient to sustain the e-beam operation up to beam current densities of *2* mA/cm$^2$.

Figure 12 shows dependence of the static temperature, static pressure, and stagnation pressure at the channel exit as functions of the e-beam power. These results show that the flow temperature in the MHD channel remains rather low, T<620 K. The significant static pressure rise (up to $P/P_i$=3.5) suggests that boundary layer separation in the channel may well become a serious issue. The predicted considerable total pressure loss (up to $P_0/P_{0i}$=0.3) is mainly due to the conversion of a part of the kinetic energy of the flow into heat (50% in this case). Heating of the flow and the resultant total pressure drop can be reduced if the loading parameter $K_{Faraday}$ is kept

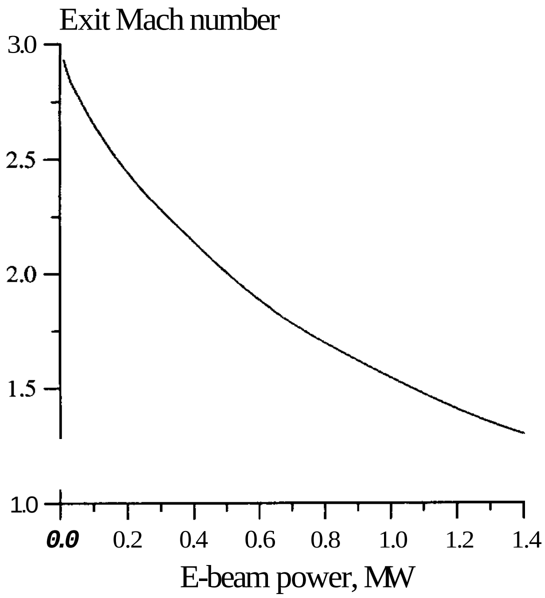


Figure 9. Exit Mach number as a function of the absorbed e-beam power. Faraday accelerator, K=0.5

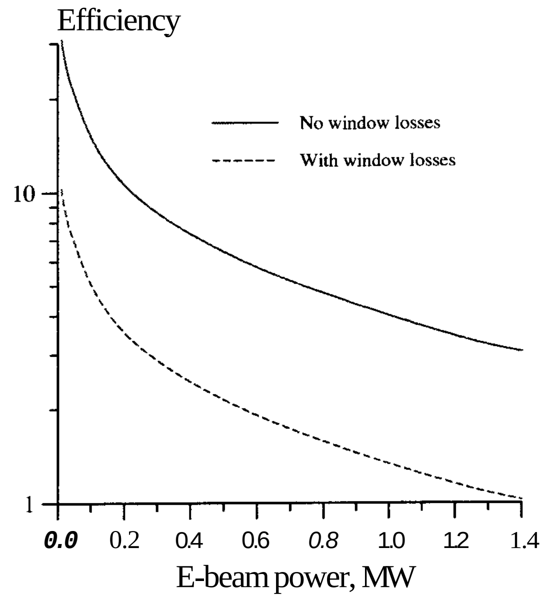


Figure 10. Generator efficiency as a function of the absorbed e-beam power, with and without window losses. Faraday accelerator, K=0.5

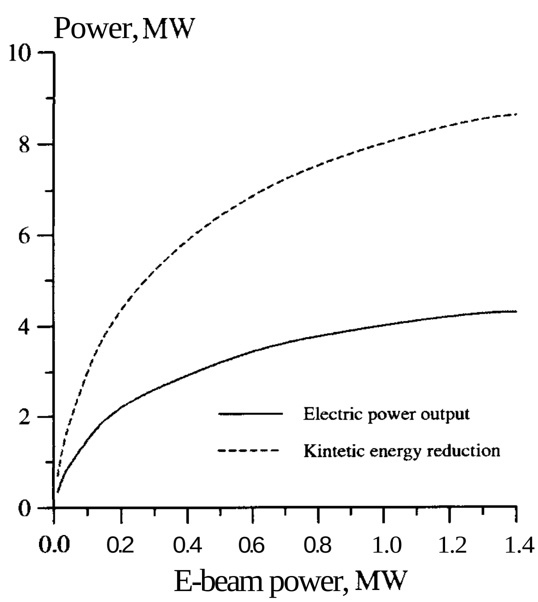


Figure 11. Extracted electrical power and kinetic energy reduction as functions of the absorbed e-beam power. Faraday accelerator, K=0.5

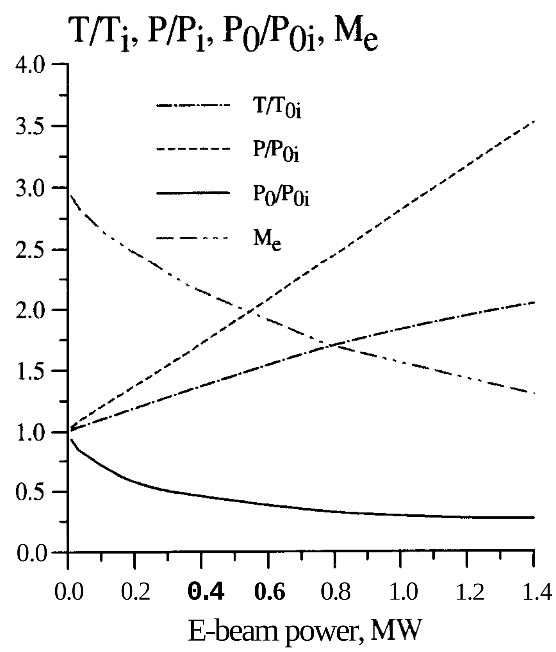


Figure 12. Static temperature and pressure and stagnation pressure as functions of the absorbed e-beam power. Faraday accelerator, K=0.5

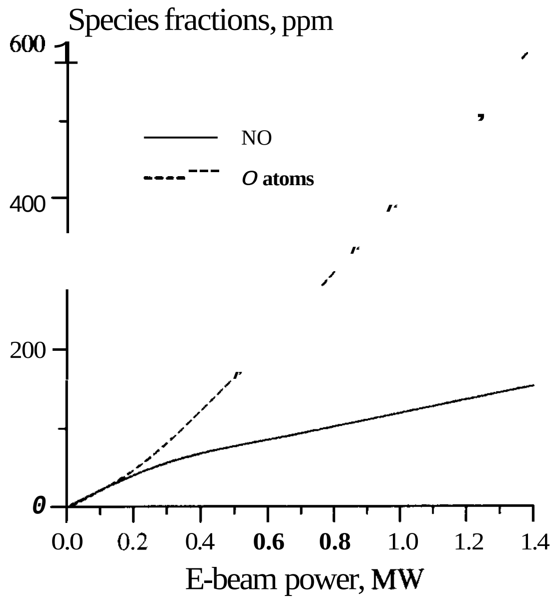


Figure 13. Exit species concentrations as functions of the absorbed e-beam power. Faraday accelerator, K=0.5

close to 1. In this case, the flow heating (i.e. the difference between the kinetic energy reduction and the electrical power produced) is reduced to minimum. However, the extracted kinetic energy at $K_{Faraday} \rightarrow 1$ is approaching zero. The compromise value of the loading parameter depends of the specific application, which may require either maximizing electrical power output or minimizing the total pressure loss.

Fig. 13 shows the dependence of the exit species concentrations (NO and **O** atoms) as functions of the e-beam power. It can be seen that increasing the beam current results in accelerating the e-beam initiated chemical processes in the MHD channel, primarily electron impact dissociation of oxygen.

### 3. Summary

The present calculations suggest that the use of electron beams with characteristics, such as electron energy (–60 keV before the window), beam current (–0.2 mA/cm$^2$), and size (–0.5 m) close to the commercially available e-beam systems to sustain ionization in intermediate pressure, low-temperature (P=0.1 atm, T=300 **K)** supersonic air flows allows considerable reduction of the flow kinetic energy (up to 10-20% in M=3 flows). The calculations suggest that this can be achieved at a reasonable electron beam efficiency ($\eta$~5), even if the e-beam window losses are taken into account. At these conditions, the exit NO and **O** atom concentrations due to e-beam initiated chemical reactions do not exceed 30 ppm. Increasing the beam current up to –2 mA/cm$^2$ ($\sigma_{max}$~0.8 mho/m at K=0.5) would result in a much greater reduction of the flow kinetic energy (up to 30-40%). The MHD channel efficiency at these conditions would be greatly reduced (to $\eta$~1) due to increased electron recombination losses in the channel. At these conditions (K=0.5), partial energy conversion from kinetic energy to heat results in a significant total pressure loss ($P_0/P_{0i}$~0.3). The total pressure loss can be reduced operating at the loading parameter closer to unity, at the expense of the reduced electrical power output. Raising the beam current would also result in the increase of the exit **O** atom concentrations (up to 600 ppm) and NO (up to 150 ppm).

For practical applications in turbojet engine diffusers, a radial rather than tangential magnetic field will be applied, $B_r$. In this case, sustaining axial current in the MHD channel operating in the Hall generator mode would also create swirl in the flow, thereby acting as a first stage of an axial compressor. However, modeling of this geometry requires developing of a two-dimensional nonequilibrium MHD flow code.

## References


1. D.I. Brichkin, A.L. Kuranov, and E.G. Sheikin, "Scramjet with MHD Control Under *AJAX* Concept. Physical Limitations", AIAA 2001-0381, presented at 39th AIAA Aerospace Sciences Meeting, January 8-11,2001, Reno NV
2. C. Bruno, P.A. Czysz, and S.N.B. Murthy, "Electro-magnetic Interactions in a Hypersonic Propulsion System", AIAA 97-3389, presented at 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 6-9, 1997, Seattle, WA
3. R.L. Chase, R. Boyd, P. Czysz, H.D. Froning, Jr., M. Lewis, and L.E. McKinney, "An AJAX Technology Advanced SSTO Design Concept", AIAA 98-5527
4. S.N.B. Murthy and I.M. Blankson, "MHD Energy Bypass for Turbojet-Based Engines", IAF-00-5-5-05, presented at 51st International Astronautical Congress, October 2-6, 2000, Rio de Janeiro, Brazil
5. S.O. Macheret, M.N. Shneider, and R.B. Miles, "Electron Beam Generated Plasmas in Hypersonic MHD Channels", AIAA 99-3635, presented at 33rd Thermophysics Conference, June 28 – July 1, 1999, Norfolk, VA
6. J. Chapman, H. Schmidt, R. Ruoff, V. Chandrasekhar, D. Dikin, and R. Litchford, "Flightweight Magnets for Space Application Using Carbon Nanotubes", AIAA 2003-0330, presented at 41st AIAA Aerospace Sciences Meeting, January 6-9,2003, Reno NV
7. I.V. Adamovich, J.W. Rich, and G.L. Nelson, "Feasibility Study of Magneto-hydrodynamics Acceleration of Unseeded and Seeded Airflows", AIAA Journal, vol. 36, No. 4, 1998, pp. 590-597
8. H. Matzing, "Chemical Kinetics of Flue Gas Cleaning by Irradiation with Electrons", Advances in Chemical Physics", ed. by I. Prigogine and S.A. Rice, vol. 80, Wiley, New York, 1991, pp. 315-403
9. P. Palm, E. Plonjes , M. Buoni, V.V. Subramaniam, I.V. Adamovich, and J.W. Rich, "Electron Beam Generated High-Pressure Air Plasmas Enhanced by Optical Pumping", AIAA Paper 2001-0346, presented at 39th Aerospace Sciences Meeting and Exhibit, January 2001, Reno, NV
10. Peter Palm, Elke Plonjes, Igor V. Adamovich, Vish V. Subramaniam, Walter R. Lempert and J. William Rich, "High-pressure Air Plasmas Sustained by an Electron Beam and Enhanced

by Optical Pumping", Paper 2001-2937, presented at AIAA 32$^{th}$ Plasmadynamics and Lasers Conference, Anaheim, CA, June 11-14,2001

11. P. Palm, E. Ploenjes, V. Subramaniam, I.V. Adamovich, and J.W. Rich, "E-beam / RF Field Sustained Low Power Budget Air Plasmas", AIAA Paper 2002-0637, presented at 40$^{th}$ Aerospace Sciences Meeting and Exhibit, January 2002, Reno, NV
12. P. Palm, E. Ploenjes, I. Adamovich, and J. Rich, "Mitigation of Electron Attachment and Recombination in Atmospheric Pressure Air Plasmas", AIAA Paper 2002-2224, presented at 33$^{rd}$ Plasmadynamics and Lasers Conference, Maui, HW, 20-23 May 2002
13. E. Plonjes, P. Palm, J.W. Rich, and I.V. Adamovich, "Electron-Mediated Vibration-Electronic (V-E) Energy Transfer in Optically Pumped Plasmas Enhanced by an Electron Beam", AIAA Paper 2003-0131, presented at 41$^{th}$ Aerospace Sciences Meeting and Exhibit, January 2003, Reno, NV
14. R.J. Rosa, "Magnetohydrodynamic Energy Conversion", New York, McGraw-Hill, 1968
15. L.E. Rittenhouse, J.C. Pigot, J.M. Whoric, abd D.R. Wilson, "Theoretical and Experimental Results with a Linear Magnetohydrodynamics Accelerator Operated in a Hall Current Neutralized Mode", Arnold Engineering Development Center, AEDC TR-67-150, Tullahoma, TN, November 1967