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## Hypersonic Engine using MHD Energy Bypass with a Conventional Turbojet

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### Abstract

This paper reports current progress and results in studies of energy extraction and bypass along the gas path of jet propulsion engines, using magneto-hydro-dynamic (MHD) processes. Specifically, an MHD bypass engine cycle incorporating conventional gas turbine technology is being explored. It may be a viable approach to both a first stage of a future two-stage-to-orbit vehicle, and to high-speed military/commercial long-range cruise vehicles. The overall research objective is to establish the feasibility and demonstrability of kinetic energy bypass from a weakly ionized inlet air stream of a turbojet. The weak, non-equilibrium ionization is provided by an external electrical means such as an electron beam. MHD interaction with the ionized gas then leads to energy bypass of the turbojet. The resulting wide operating range engine consists of an existing commercial or military jet engine preceded by an MHD power generator. The resulting revolutionary engine would power a vehicle capable of flight from takeoff to Mach 7 during which the turbojet operates continuously over this entire flight regime. The specific MHD inlet design under study is an annular generator/accelerator concept (patent pending). Its embodiment has a superconducting magnet in a configuration similar to that of a Hall Thruster for space applications. Our research efforts include defining the operating conditions for an MHD bypass turbojet cycle, developing a viscous compressible MHD flow code with real-gas effects for flow analysis, air ionization technique assessment, MHD interaction tests, component conceptual design, and a test plan for a generator-turbojet combination in an appropriate wind-tunnel facility.

### I. Introduction

NASA is currently engaged in research to develop low-cost alternatives for access-to-space and novel concepts for high Mach number propulsion. In recent years, plasma flows have rapidly become the basis of new technologies that find application to hypersonic propulsion. It is anticipated that combining technology developments in electromagnetics, aerodynamics, and chemical kinetics may lead to a breakthrough for improving aerospace vehicle performance. Besides the traditional use of plasmas in space thrusters, a growing interest is evident in plasma-based aerodynamics, including flow manipulation through MHD (magnetohydrodynamic) forces, power generation, and drag reduction (Refs. 1-7). An integrated combined cycle propulsion system incorporating turbomachinery and MHD, our primary area of interest, can be used in both aircraft and aerospace planes. The objective of the present work is to study the 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 an MHD diffuser for a turbojet engine (Ref. 4). An important goal is to determine whether ionization efficiently generated in a supersonic flow using a high-energy electron beam can be used to produce a Lorentz force of a magnitude sufficient to generate substantial amounts of electrical power, and to considerably reduce the kinetic energy of the flow.

This paper reports current progress and results in studies of energy extraction and bypass along the gas path of jet propulsion engines, using magneto-hydro-dynamic (MHD) processes. Two

types of engines are considered: (1) a mixed-flow turbofan engine of the class utilized in military applications, with an after-burner, and (2) a turbo-ramjet engine operating on the expander cycle, that can be utilized in, among others, a space transportation scheme in the flight Mach number range  $M_0 = 0 - 7$ . The main interest is in establishing the feasibility of undertaking an on-ground demonstration-test of the feasibility and effectiveness of applying MHD processes over the engine flowpath with local external ionization of the working fluid. The MHD processes permit a direct conversion of working fluid total energy (kinetic energy and enthalpy) into electrical power and, in principle, the reuse of that power for thrust generation by direct acceleration of the working fluid; other uses of the electrical power include, for example, heating and ignition. Such energy conversion and reuse may be undertaken in several components of the two types of engines considered, for example in the inlet, the combustor, and the nozzle (the stationary components) and ducting attached to them.

Shown schematically in Figure 1a is an MHD driven energy bypass engine using a turbojet. The MHD generator may be employed in the inlet, nozzle, and another duct, individually and in combination. The possibility of electromagnetically extracting part of the turbojet inlet air kinetic energy is the key feature. The concept potentially offers variable inlet geometry performance without the complexity of moving inlet parts. Three primary aeropropulsion purposes are served by the concept. Firstly, the flow enthalpy into the combustor is reduced allowing more efficient addition of energy in the combustor without exceeding temperature limitations on the turbine materials. Secondly, the applied electromagnetic fields and their body forces can enhance off-design performance by manipulating the flow features in the supersonic/hypersonic inlets thereby reducing total pressure losses and entropy changes for the same level of flow compression by other means. Thirdly, 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 electromagnetic 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. At present, there are considerable ambiguities on the actual process of ionization, the effectiveness of different means, and the resulting state of plasma.

It may be pertinent to recall that mass and energy bypass is a common feature in many classes of engines with the use of bypass fan, pre-cooler, inter-cooler, and heat exchanger for air and fuel. In all cases, the two significant factors governing their use are (1) effectiveness in improving thrust specific fuel consumption (TSFC) and (2) their size, volume and mass, affecting the specific volume and mass of the engine. The applicability of MHD processes in a practical engine needs emphasis on the same factors. Some related considerations that also arise from effectiveness and size considerations on practical application are system integration and control. However, none of these considerations is critical to the demonstration tests.

In the current study, the initial objectives in the case of the turbofan engine are three-fold, all of them related to the demonstration-test: (1) establishment of the extent of diffusion of air that can be obtained by energy extraction with MHD processes; (2) establishment of the feasibility of operating the system with the working fluid in a weakly ionized state; and (3) examining various schemes for bypass and reuse of the extracted energy. In the case of the turboramjet engine, the objectives are the same with a greater emphasis on the high Mach number regime. This study program has just started, and the current paper provides the conceptual framework for demonstrating this technology with reference, somewhat unavoidably, to specific detailed design of the test engines.

In addition to the above work, a parallel effort is developing a multidimensional CE/SE code capable of computing viscous compressible MHD flows with real-gas effects (Ref. 8-9). Aspects of the flow that are critical to CFD modeling include chemical reactions, ionization and electrical conductivity, thermal nonequilibrium, wall boundaries, electrical field generation, Hall effect, turbulence and flow separation, transport processes, etc. Furthermore, an electric field is induced by the flow of current through the magnetic field, and this causes a coupling between the equations of fluid mechanics (Navier-Stokes equations) and the equations of electromagnetics (Maxwell equations). In various cases of engineering importance, this coupling is ignored by assuming that the induced electric field is small. This is hardly the case in the engine system considered here.

## II. Flowpath Design and Description of Components

The generation of energy from the engine gaseous working fluid involves conversion of the thermal and kinetic energy of the fluid, and, therefore, gives rise to a change in both the gas temperature and pressure, in addition to velocity (and Mach number). Considering the possibility of subsonic and supersonic flow speeds along the gas flowpath in different cases and locations, the geometry of the flowpath becomes a significant parameter in the design and performance estimation of the generator. These considerations obviously also arise during input of energy back to the working fluid, whether to accelerate it and derive thrust output, or simply to add thermal energy to it.

A general arrangement of an MHD controlled turbojet for high-speed propulsion is shown in Fig. 1a. The critical elements are the MHD generator, shown in more detail in Fig. 1b, and the MHD controlled Mach 3 variable flow geometry inlet. These two elements may, of course, be part of the same physical unit. The general problems and issues encountered in the deceleration of supersonic and hypersonic flows by applied magnetic fields have been considered by various authors. Detailed discussions and analyses may be found in the paper by Vatazhin (Ref. 10) and, more recently, the publication by Bobashev (Ref.11). The ability to manipulate the off-design performance of hypersonic inlets using MHD could have major benefits in aerospace vehicle design. The use of an existing operational turbojet is a desired aspect of this arrangement. For the ground-test evaluation shown schematically in Fig. 1c, an engine of the Allison J-102 class is desirable and may be situated inside or outside the wind-tunnel. A critical technology necessary for the implementation of this concept is lightweight cryogenic magnet technology. Recently, superconducting properties of carbon nanotubes have been measured Ref. [12] offering the possibility of lightweight cryogenic magnets for aerospace applications.

The annular flowpath geometry of a turbojet suggests the desirability of an annular type MHD power extraction/addition device for energy bypass of the turbojet. An annular Hall type generator concept is shown in Figure 1b. It has an externally applied radial magnetic field throughout the volume of the annulus. When an ionized gas flows through this annulus with its applied magnetic field, an azimuthal Hall current is driven. This current further interacts with the magnetic field to set up an axial electric field known as the Hall voltage. There are no segmented electrodes in this design to stand off this voltage as used in linear Hall generators (Ref. 13-14). The azimuthal current short circuits through the plasma around the annulus instead of through segmented electrodes. There are only two electrodes at the entrance and exit of the annulus with insulator wall in between. The load or axial electric field applied across these electrodes determines the MHD interaction (energy extraction/addition) with the flow. In the proposed concept, the load current flows in a "spiral curtain" of conductivity shaped like an auger in the annular passage as shown in Figure 1b. 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 non-equilibrium MHD flow code. The conductivity is generated by opposed electron beam guns as presented in Ref. [6] 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.

This geometry was explored briefly for stationary combustion driven MHD power generation (Ref. 15) in the 1950s. The interaction experiments were conducted with combustion products seeded with potassium to enhance the conductivity. The generator delivered disappointing results because of loss of conductivity due to electron-water molecule interactions and short circuiting through the higher conductivity boundary layers. The turbojet application uses high altitude dry air and non-thermal ionization in the core flow to alleviate these known problems. The geometry was successfully developed into the Stationary Plasma Thruster for space propulsion by the Russians using very low pressure xenon plasmas and is flying on the Russian Express satellite (Ref. 16).

### III. CE/SE CFD Computational Development

In addition to the above work, a parallel effort is developing a multidimensional CESE code capable of computing viscous compressible MHD flows with real-gas effects (Ref. 9). Aspects of the flow that are critical to CFD modeling include chemical reactions, ionization and electrical conductivity, thermal nonequilibrium, wall boundaries, electrical field generation, hall effect, turbulence and flow separation, two phase effects, seeding efficiency, transport processes, etc. Furthermore, electric field is induced by the flow of current through the magnetic field, and this causes a coupling between the equations of fluid mechanics (Navier-Stokes equations) and the equations of electromagnetics (Maxwell equations). In various cases of engineering importance, this coupling is ignored by assuming that the induced electric field is small. This is hardly the case in the engine system considered here. In a series of publications (e.g. Ref. 8), Chang and coworkers successfully developed a new numerical framework, namely the Space-Time Conservation Element and Solution Element (CESE) method, for linear and nonlinear convection-diffusion equations in one, two, and three spatial dimensions. Numerous results, obtained by using the CESE method, have been reported in the cited references, including flows with steady and moving shock, rarefaction waves, and acoustic waves, flows dominated by vortices, detonating flows, shock/acoustic waves/vortices interactions, dam-break flows, hydraulic jump, cavitating flows, and the turbulent flows with embedded sprays.

The interest in solving the MHD equations by the CESE method arises from the possibility of exploiting certain inherent properties of the CESE method. By treating space and time as one entity, the MHD equations are formulated in a space-time integral form. As a contrast to the modern upwind methods, no reconstruction procedure or Riemann solver is needed in this approach. The computational logic and operational count of the present approach are much simpler and more efficient. Moreover, no special treatment has been employed to maintain the divergence-free condition for the magnetic field. Nevertheless, due to strict space-time flux conservation achieved by the CESE method, the  $\nabla \cdot \mathbf{B} = 0$  condition is well maintained in the smooth region. In the region near shock waves, the  $L_1$  norm of  $\nabla \cdot \mathbf{B}$  is bounded. Several one and two dimensional benchmark problems have been calculated. Recent results of propagating MHD shock and expansion waves in one and two spatial dimensions showed remarkable numerical resolution. The CFD development is expected to be a long term research project, beginning with the treatment of the ideal MHD equations.

Due to the complexity of the MHD problems, a highly accurate but simple method is desired. This is particularly important for extending the solvers to model complex MHD processes, in which the model equations could include multiple fluids with chemical reactions. In the present paper, we report on the progress made in the numerical construction of solution of the ideal MHD equations by the CESE method as the first step for the development of a general numerical framework for complex MHD models. The initial calculations and results may be found in Refs. 9 and 22. Based on special features of the CESE method, it is shown that (i) no Riemann solver is needed, and (ii) no special treatment is employed to satisfy the  $\nabla \cdot \mathbf{B} = 0$  constraint. Due to these two special features, the CESE method could be a promising method as a general numerical platform for complex MHD model equations. Ultimately, a complex CFD code that combines electromagnetics and real-gas phenomena will be realized based on the CESE method.

#### IV. OSU-Code Calculations

Several sets of calculations have been performed using a quasi-one-dimensional nonequilibrium MHD air flow code developed at OSU under NASA sponsorship. The code incorporates a 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. OSU is also conducting laboratory-scale tests to experimentally establish the efficiency of the MHD conversion of the kinetic energy of externally ionized gas in the proposed bypass engine scheme. Details of OSU research are summarized in Refs. 6 and 17-21.

Initial exploratory calculations were 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 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,  $M=3.0$  ( $U=1100$  m/s). This approximately corresponds to the conditions downstream of a mild oblique shock (deflection angle  $12^\circ$ , wave angle  $25^\circ$ , free stream Mach number  $M_\infty=3.8$  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 (electron energy after the electron gun window) at the given inlet density and pressure is approximately 12 cm, 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 large 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 the reasonable beam current density of 0.2 mA/cm<sup>2</sup>. For comparison, in the on-going experiments at the Nonequilibrium Thermodynamics Group, they routinely use a Kimball Physics 80 keV e-beam (energy before the window) with current densities up to 1 mA/cm<sup>2</sup>. The window losses are approximately 40 keV across the 25  $\mu$ m aluminum foil window. The stopping distance of the resultant  $\sim 40$  keV beam is estimated to be  $\sim 3$  cm in 1 atm air (or  $\sim 30$  cm in 0.1 atm air). The length of the Kimball Physics electron gun is  $\sim 0.5$  m. This illustrates that the e-beam parameters used in the present calculations are consistent with the existing electron beam systems. A uniform magnetic field  $B_0=10$  T is applied in the annulus.

From Figure 2a, it can be seen 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) or  $\eta=1$  (with

window losses). Figure 2b 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 electric conductivity. These initial calculations suggest that the use of electron beams with realistic characteristics close to the existing e-beam systems to sustain ionization in intermediate pressure, low-temperature supersonic air flows allows considerable reduction of the flow kinetic energy.

More detailed calculations were made to illustrate the performance differences of Faraday and Hall configurations in Fig 3. A uniform tangential magnetic field  $B_0=10$  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,  $J_z$ . 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  $K_{\text{Faraday}}=E_y/u_z B_r$  and  $K_{\text{Hall}}=E_z/\beta u_z B_r$  (here  $\beta$  is the Hall parameter). For the Faraday generator,  $K=1$  corresponds to the open circuit regime (electrodes are disconnected from the load), and  $K=0$  is the short circuit regime (opposing electrodes are shorted). For the Hall generator,  $K=1$  is also the open circuit regime and  $K=0$  is the short circuit regime.

The results for different values of the loading parameter are summarized in Figs. 4-7. 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  $K_{\text{Faraday}}=K_{\text{Hall}}=0.5$  and the efficiency of  $\eta=15$ ) and the power converted from kinetic energy to heat (up to 5.0 MW at  $K_{\text{Faraday}}=0$  and  $K_{\text{Hall}}=1$ ). 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% ( $K_{\text{Faraday}}=0$  and  $K_{\text{Hall}}=1$ ). The initial flow power (total enthalpy times mass flow rate) is 24.1 MW at the mass flow rate of  $\dot{m}=36.6$  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  $\mu\text{m}$  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 ( $K_{\text{Faraday}}=1-K_{\text{Hall}}=0.5$ , electrical power output is maximum) and as a flow decelerator ( $K_{\text{Faraday}}=1-K_{\text{Hall}}=0$ , 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  $K_{\text{Faraday}}=0$ ,  $K_{\text{Hall}}=1$  (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,  $J_r$ , greatly exceeds the axial current,  $J_z$ , and the axial electric field,  $E_z$ , 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  $200 \text{ mA/cm}^2$  would correspond to the total current of about 5,000 A, and the open-circuit axial field of  $1300 \text{ V/cm}$  would correspond to  $130 \text{ kV}$  total voltage. These conditions correspond to the flow electrical conductivity of up to  $\sim 0.4 \text{ mho/m}$ , which is considerably lower than the conductivity typically achieved in high-temperature MHD flows, up to a few tens of  $\text{mho/m}$ . 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  $E/N=0.5 \cdot 10^{-16} \text{ V}\cdot\text{cm}^2$  (the breakdown voltage is  $\sim 10^{-15} \text{ V}\cdot\text{cm}^2$ ). Note that at these high values of the Hall parameter ( $\beta \gg 1$ ), the Hall generator characteristics are very close to the ones for the Faraday generator at  $K_{\text{Faraday}}=1-K_{\text{Hall}}$  (see Figs. 4-7). Indeed, in this case the magnitudes of the Lorentz force for the two schemes are very close,

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

The present calculations suggest that due to the 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.

## V. Ground Demonstration Scheme.

A desired result of this work is to outline a method of conducting a test on a jet engine for demonstrating and assessing the performance of a MHD energy bypass system incorporated into a jet engine. Current activities include analyses and simulation of several schemes that are under consideration. A demonstration test can be organized as shown in the schematic in Fig. 1c, which includes a wind tunnel with a Mach range of about 0.8 to 4.0 with variable stagnation conditions, a variable magnetic field of field intensity 1 to 3 Tesla, and a flow ionizing scheme for obtaining electrical conductivity in the range 1 to at least 50 mhos/m. The ducting ahead of the inlet is placed in the wind tunnel and the rest of the engine, including the turbofan is located outside the wind tunnel. The wind tunnel airflow is to be heated and pressurized so that following energy extraction and pre-cooling, the inlet is able to provide airflow to the engine under desired engine operating conditions. In Ref. 5, selected trajectories for flight vehicles incorporating a turbojet and a ramjet engine were analyzed for modest to optimistic values of the gas conductivity for several cases of inlet conditions. This on-going research has resulted in the development of an integrated model for a jet engine with energy bypass for determining the design and operating conditions in which the thrust-to-weight ratio, thrust per unit mass of fuel consumption, and effectiveness of energy utilization are maximized. Parametric studies using electrical conductivity, magnet mass, and MHD energy conversion have been made to assess engine thrust-to-weight ratio and thermodynamic efficiency.

The engine design and operational conditions are required to be known in substantial detail before a test plan can be set up. The inclusion of a precooler in the test set up is based on regulating the engine entry temperature such that, with the pressure loss in the MHD generator and the precooler, the engine nondimensional mass flow and rotational speed are matched. The heater is added as part of the engine cycle for energizing the bypass air. As stated earlier, the MHD power

may be utilized for direct acceleration of a flow or for energizing it. A direct use requires a substantial ionizer and applied B-field, with  $K$  greater than unity, especially when the velocity is relatively low; in the case of the fan engine, the mixing duct diameter may be around 0.5m. A flow accelerator demonstration is not considered here. Meanwhile, the addition of the heater does not affect the rest of the engine cycle in either case. A major consideration in the demonstration tests is the power balance among the ionizer, MHD generator, and engine without and with the heater in the bypass air stream. This depends chiefly on the ionizer power requirement, which still is to be established. Another major consideration is the feasibility of using the Lorentz force ( $\mathbf{F}_L = \mathbf{J} \times \mathbf{B}$ ) directly for air compression. Under the given conditions, the Lorentz force in the generic example is about 1 kN over the length of 1 m with  $K = 0.9$ : with  $\eta_{EN} = 0.1$ , this force would only provide a negligible change in stagnation pressure. The change in other state properties and velocity depend on the details of the duct geometry. A change in stagnation pressure of 10%, under otherwise same conditions, requires a doubling of the B-field and a flow velocity no less than about 300 m/s; with a duct designed for isothermal flow (220 K), this would correspond, under no duct heat loss, to a change in velocity of about 100 m/s.

While the foregoing estimates provide a starting point for the feasibility study, several refinements are mandatory before setting up a demonstration test that is expected to be neither simple nor inexpensive:

- ionization of flow, both in the estimation of conductivity realizable with various schemes of ionization and the feasibility of obtaining a specific conductivity value over a desired, effective flow channel area;
- accounting for viscous and turbulence effects in the ducting;
- magnetic field generation and the associated volume and mass associated with it; and
- engine design constraints for utilizing the technology for flow diffusion and compression and power production.

## VI. SUMMARY

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 non-equilibrium supersonic airflows, with the primary application being an MHD diffuser for a turbojet engine. The main purpose of the present study is to determine whether the ionization efficiently generated in a 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.

The modeling calculations have been performed using the quasi-one-dimensional nonequilibrium MHD air flow code developed at OSU (Ref. 6). The calculations suggest that the use of electron beams with characteristics, such as electron energy ( $\sim 60$  keV before the window), beam current ( $\sim 0.2$  mA/cm<sup>2</sup>), and size ( $\sim 0.5$  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 ( $\eta \sim 5$ ), 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  $\sim 2$  mA/cm<sup>2</sup> ( $\sigma_{\max} \sim 0.8$  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  $\eta \sim 1$ ) 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 ( $P_0/P_{0i} \sim 0.3$ ). 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). In addition to the above work, a parallel effort is developing a multidimensional CESE code capable of computing viscous compressible MHD flows with real-gas effects (Ref. 9). Results of a sample calculation, a 2D MHD vortex, is presented in Figure 8.

The changes in the state properties of the flow in various cases depend on the specific geometry employed for the MHD process duct, and the friction and heat transfer losses. For example, the ducting may have an area change for obtaining a constant value for one of the properties or the duct area of cross-section. In every case the engine performance will change compared to that without energy extraction. The details of those changes can be determined only with details of engine design. A few observations may be made here:

- In the flow ahead of the engine face, a stagnation temperature drop due to power extraction is accompanied by a much larger stagnation pressure drop, and this may be entirely unacceptable in most engines. Even in a demonstration test, such changes necessitate substantial variability in the temperature and pressure of the supply air at different inflow Mach numbers.

The energy extraction in the flow at the nozzle end is easier to handle, although this causes in many cases large changes in engine overall pressure ratio and the pressure ratio of bypass air, as well as other parameters.

- The flow electrical conductivity is assumed to be uniform over the interaction volume, and this will need a substantial input of power into the ionizer, and possibly an innovative new ionization scheme.

- Finally, the increase in the volume and mass of the engine needs to be compared with other schemes of diffusing and cooling airflow.

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## General Arrangement of MHD Controlled turbojet High-Speed Propulsion

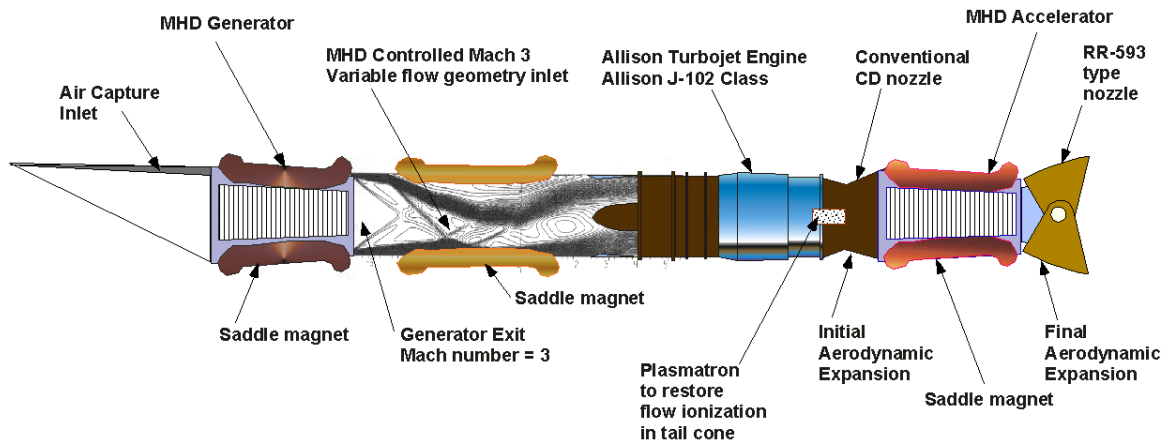


Figure 1a: MHD Energy Bypass System Incorporating Jet/Gas Turbine Engines.

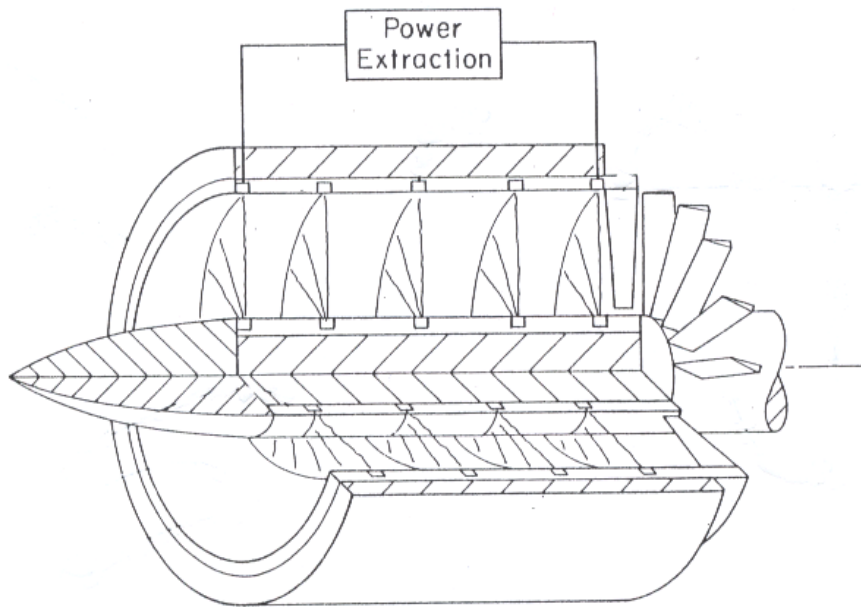
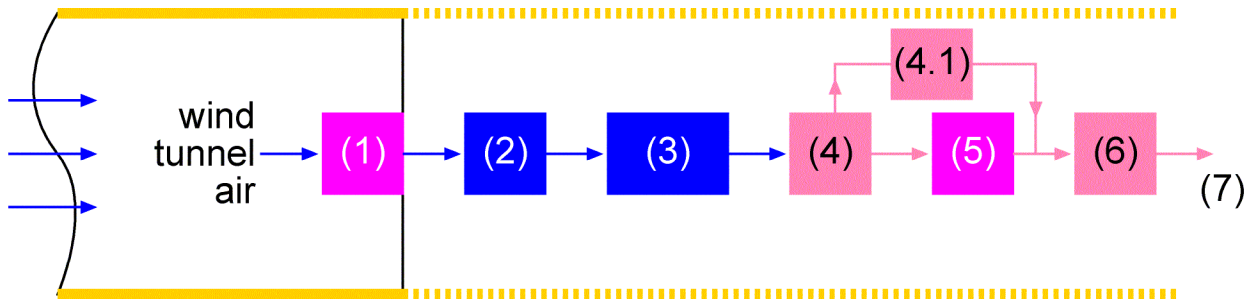


Figure. 1b: Annular **H**all type MHD power extraction concept for the inlet of a turbojet.

Figure 1c: Ground-test Demonstration Scheme



- (1) inlet air MHD power generation duct
- (2) pre-cooler
- (3) engine inlet
- (4) engine
- (4.1) air heater
- (5) hot gas MHD power generation duct
- (6) thrust nozzle
- (7) ambient surroundings

Figure 3. Demonstration Test Scheme.

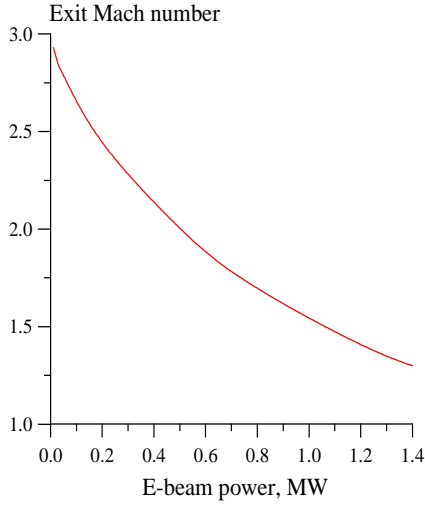


Figure 2a: Exit Mach number as a function of the absorbed e-beam power.

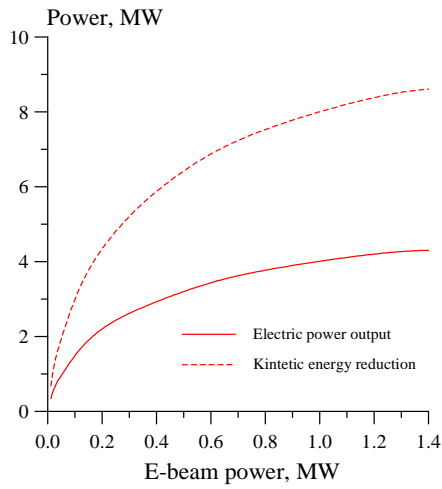
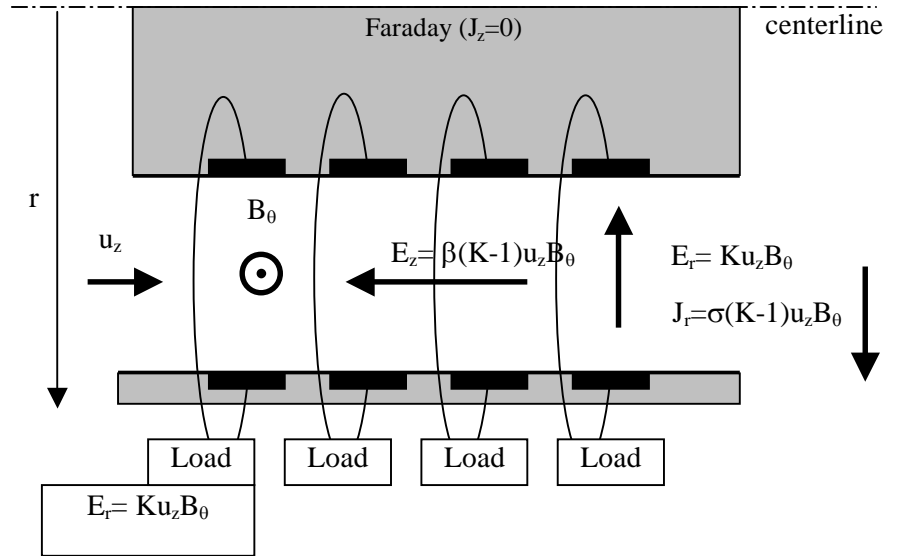


Figure 2b: Extracted electrical power and kinetic Energy reduction as functions of absorbed e-beam Power.

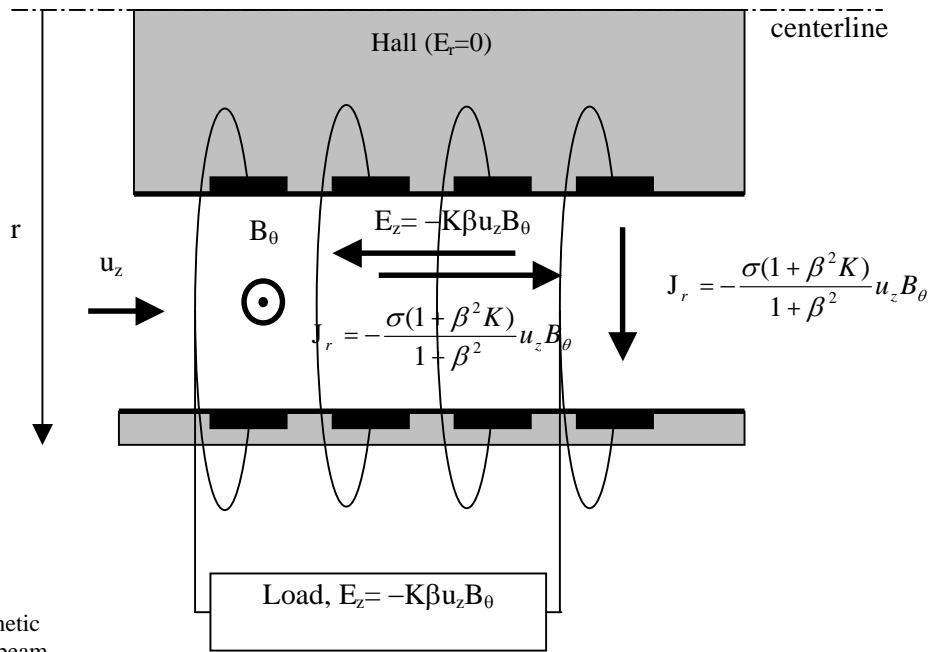


Figure 3. Electrode configurations for the Faraday and Hall accelerators.

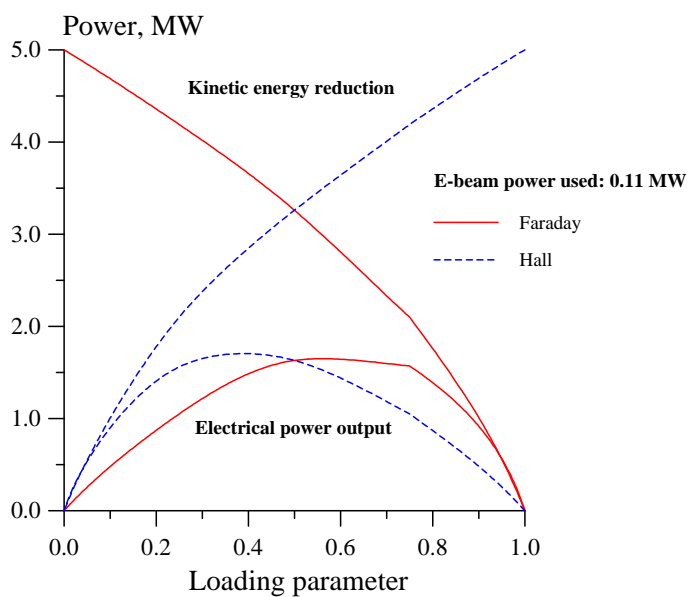


Figure 4. Extracted electrical power and kinetic energy reduction as functions of the loading parameter. E-beam load is 1 eV/molecule/sec

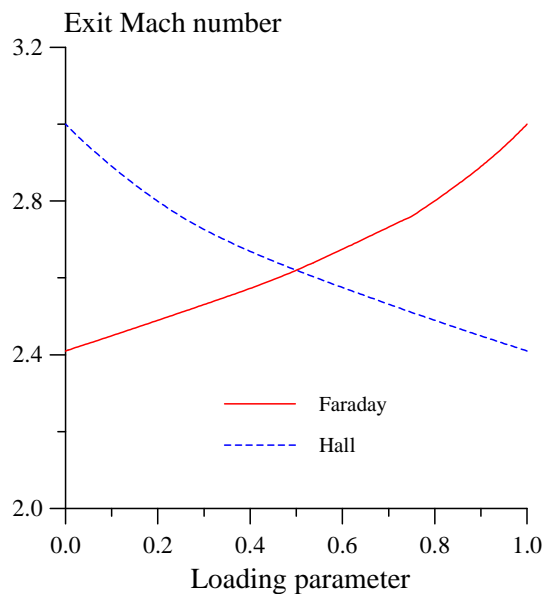


Figure 5. Exit Mach number as a function of the loading parameter. E-beam load is 1 eV/molecule/sec

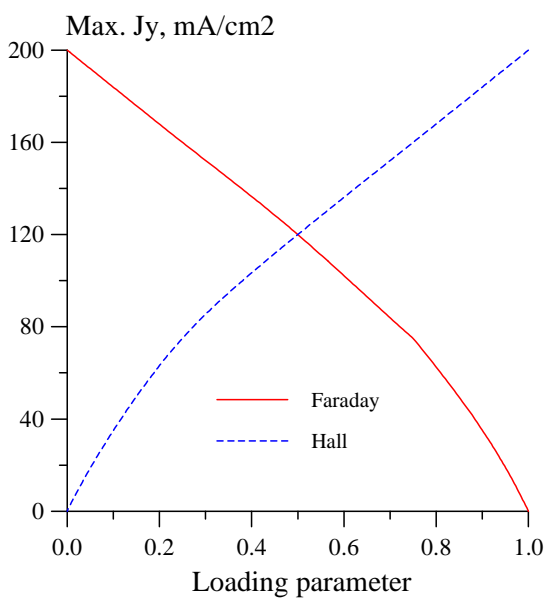


Figure 6. Maximum transverse current density as a function of the loading parameter. E-beam load is 1 eV/molecule/sec

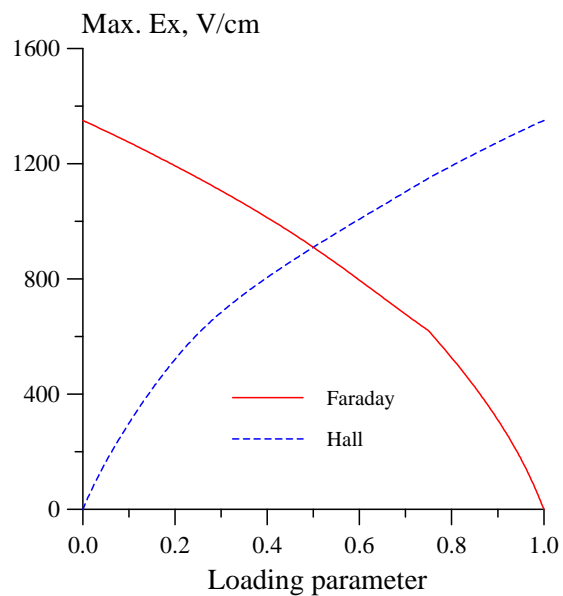


Figure 7. Maximum axial electric field as a function of the loading parameter. E-beam load is 1 eV/molecule/sec

# MHD Vortex

- Computational domain:  $[0, 2\pi] \times [0, 2\pi]$
- Initial condition:  
 $\rho(x, y, 0) = \gamma^2, p(x, y, 0) = \gamma$   
 $u(x, y, 0) = -\sin y, v(x, y, 0) = \sin x, w(x, y, 0) = 0$   
 $B_x(x, y, 0) = -\sin y, B_y(x, y, 0) = \sin 2x, B_z(x, y, 0) = 0$

- Periodic boundary condition.
- 385x385 mesh in spatial domain.
- Total time is 10.

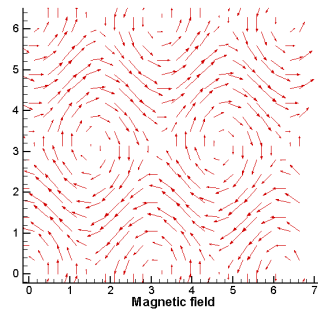
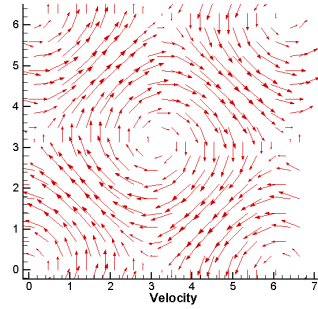
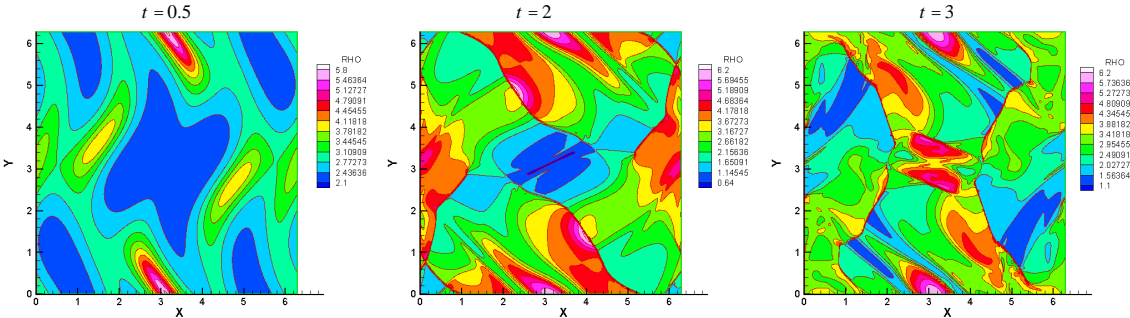


Figure 8a. The 2D MHD Compressible Vortex due to Orszag and Tang. Flow involves a complex evolution due to interactions between shock waves and vortices. Computational domain and initial conditions show in figure.

# Density Contours

CESE results



WENO results from Jiang and Wu JCP 1999

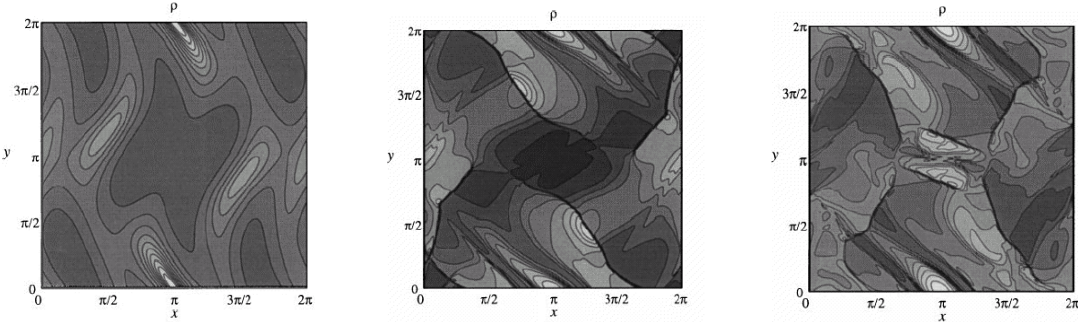


Figure 8b. Density Contours of MHD vortex calculated by CESE Method compared with Jiang and Wu's (Ref. 23) WENO method. (See Ref. 22 for further details)