Flow Matching Results of an MHD Energy Bypass System on a Supersonic Turbojet Engine Using the Numerical Propulsion System Simulation (NPSS) Environment

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Abstract

Flow matching has been successfully achieved for an MHD energy bypass system on a supersonic turbojet engine. The Numerical Propulsion System Simulation (NPSS) environment helped perform a thermodynamic cycle analysis to properly match the flows from an inlet employing a MHD energy bypass system (consisting of an MHD generator and MHD accelerator) on a supersonic turbojet engine. Working with various operating conditions (such as the applied magnetic field, MHD generator length and flow conductivity), interfacing studies were conducted between the MHD generator, the turbojet engine, and the MHD accelerator. This paper briefly describes the NPSS environment used in this analysis. This paper further describes the analysis of a supersonic turbojet engine with an MHD generator/accelerator energy bypass system. Results from this study have shown that using MHD energy bypass in the flow path of a supersonic turbojet engine increases the useful Mach number operating range from 0 to 3.0 Mach (not using MHD) to a range of 0 to 7.0 Mach with specific net thrust range of 740 N-s/kg (at ambient Mach = 3.25) to 70 N-s/kg (at ambient Mach = 7). These results were achieved with an applied magnetic field of 2.5 Tesla and conductivity levels in a range from 2 mhos/m (ambient Mach = 7) to 5.5 mhos/m (ambient Mach = 3.5) for an MHD generator length of 3 m.

Nomenclature

γ	specific heat ratio for air
$\eta_{N(a)}$	enthalpy addition ratio of the MHD accelerator
$\eta_{N(g)}$	enthalpy extraction ratio of the MHD generator
$\eta_{s(a)}$	isentropic efficiency for the MHD accelerator
$\eta_{s(g)}$	isentropic efficiency for the MHD generator
π_a	stagnation pressure ratio of the MHD accelerator
π_g	stagnation pressure ratio of the MHD generator
π_p	stagnation pressure ratio of the pre-ionizer
σ	electrical conductivity
χ	fraction of MHD generator power diverted to pre-ionizer
A_g	cross sectional area of the MHD generator
B	magnetic field intensity
C_p	constant pressure specific heat
K	Faraday loading parameter
L	length of the MHD generator
$\dot{m}$	mass flow rate of the air and fuel through the turbojet
M_{entrance}	Mach number at the entrance of a component
M_{exit}	Mach number at the exit of a component
P_{elec}	power output of the MHD generator
P_{elecA}	power input into the MHD accelerator
$T_{0,12}$	stagnation temperature at the entrance of the MHD generator

$T_{0,14}$	stagnation temperature at the exit of the MHD generator
$T_{0,58}$	stagnation temperature at the entrance of the MHD accelerator
$T_{0,6}$	stagnation temperature at the exit of the MHD accelerator
$T_{0,entrance}$	stagnation temperature at the entrance of a component
$T_{0,exit}$	stagnation temperature at the exit of a component
v	velocity of flow

Introduction

The magnetohydrodynamic (MHD) energy bypass system has been proposed (Ref. 1) to provide benefits for aeropropulsion systems. It is anticipated that combining technology developments in electromagnetics, aerodynamics, and chemical kinetics may lead to a breakthrough for improving aerospace vehicle performance. A growing interest is evident in plasma-based aerodynamics including flow manipulation through MHD forces, power generation, and drag reduction. An integrated combined cycle propulsion system incorporating turbomachinery and MHD can be used in both aircraft and aerospace planes. One aspect of incorporating MHD within turbomachinery is the fact that electromagnetic fields may be used to control expanding flows in high speed nozzles to augment the thrust generated. An MHD energy bypass system bypasses kinetic energy (in the form of electrical power) from the inlet stream and uses it downstream to generate thrust or reduce drag on the vehicle. This energy bypass is accomplished by using weak ionization of the inlet stream by an external means and MHD interaction with the ionized gas. The key feature of the engine lies in the additional hardware surrounding the jet engine. Figure 1 shows a schematic of the MHD energy bypass system installed around a turbojet engine. There are three main components of an MHD energy bypass system; the pre-ionizer, the MHD generator and the MHD accelerator as shown in Figure 1. The additional MHD components are installed around an existing supersonic turbojet engine where the pre-ionizer/MHD generator pair is installed before the inlet and the pre-ionizer/MHD accelerator pair is installed after the nozzle of the engine. The following paragraphs describe the functions of each MHD component.

MHD Pre-Ionizer

The pre-ionizer for the MHD generator ionizes the flow coming into the MHD generator and is positioned downstream of the supersonic turbojet engine's inlet. There are many methods of ionizing the airflow such as high voltage nanosecond discharge, fast ionization wave array, and seeding the airflow with alkali metals. The resulting ionized flow in conjunction with an applied magnetic field provides the benefits of flow control. The pre-ionizer for the MHD accelerator is positioned downstream of the supersonic turbojet engine's nozzle and operates in a similar manner as the pre-ionizer for the MHD generator.
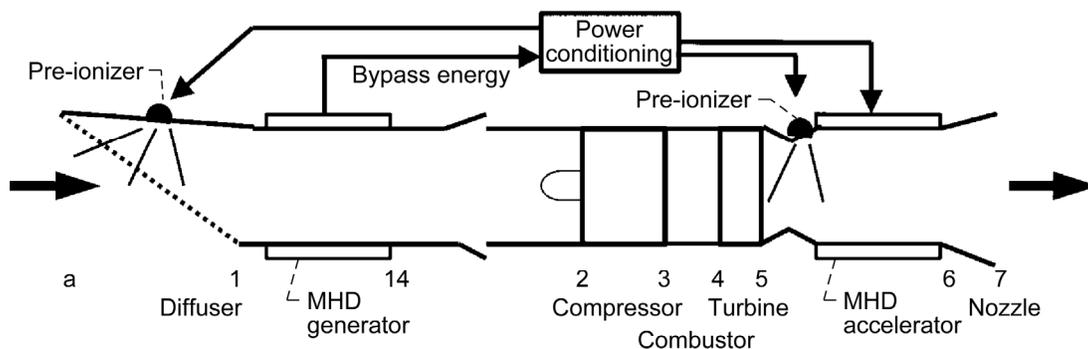
Figure 1.—Schematic of MHD controlled turbojet for high-speed propulsion.

MHD Generator

The MHD generator towards the front of the engine acts as a flow control device and provides power to the pre-ionizers and MHD accelerator. The electromagnetic fields produced by the MHD generator are used to enable variable inlet flow control that is similar to that controlled by variable geometry. The MHD generator is a non-obstructing means of total temperature reduction that can be controlled by applied magnetic fields, conductivity levels, length of the generator, and load parameter adjustment. 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.

MHD Accelerator

Most of the electrical power generated by the MHD generator is bypassed to the MHD accelerator at the back of the engine. As a result, the MHD accelerator is able to accelerate the flow exiting the engine by applying electromagnetic forces to the ionized flow and works together to augment the thrust generated.

Benefits of MHD Energy Bypass

Two primary aeropropulsion purposes are served by the MHD energy bypass concept described here. Firstly, 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, 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.

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.

The work performed with this analysis will contribute to the following goals:

1. Cycle Analysis—Conduct cycle analyses to establish the operating conditions for a jet engine cycle that are optimal for kinetic energy transfer from inlet air to a downstream location in the engine.
2. Flowpath Design—The geometry of a flowpath operating from Mach 0 to Mach 7 is to be determined. The resulting thermodynamic efficiency is to be determined using electrical conductivity, magnetic field, and MHD energy conversion as some of the parameters.

Numerical Propulsion System Simulation

To achieve flow matching between the MHD components and a supersonic turbojet engine, a comprehensive thermodynamic cycle analysis environment is needed. Previous work (Ref. 2) in flow matching provided preliminary results for MHD energy bypass on a supersonic turbojet engine and showed that MHD energy bypass is a viable technique for expanding the operating envelope of a supersonic turbojet engine. The Numerical Propulsion System Simulation (NPSS) (Refs. 3 and 4) created

at NASA Glenn Research Center is one such environment that can properly match the flows between all the elements (inlet, compressor, burner, turbine, nozzle, etc.) of an aeropropulsion system. NPSS can realistically model the physical interactions that take place throughout an aeropropulsion engine, accelerating the concept-to-production development time and reducing the need for expensive full-scale tests and experiments.

NPSS is structured in a way that allows an object oriented approach of simulating aeropropulsion systems. Due to the complex interactions between the engine components as well as large changes in environmental operating conditions, computer codes are required to predict the performance of all but the most simple, ideal engine. NPSS is one such code and its object-oriented nature enables nearly any conceivable engine architecture to be modeled accurately. One such example of a turbojet engine architecture (Ref. 5) is illustrated in Figure 2. Each grey box and each white box represents an element within NPSS. A grey box indicates the element is an actual engine component and a white box indicates the beginning, ending, or performance conditions of the NPSS propulsion system being modeled. The links connecting the grey and white boxes represent the connection within NPSS that passes the flow conditions from one element to the next. The FS labels represent the name of each flow station. The remaining link types represent a fuel port connection or a shaft port connection. For instance, in Figure 2, the power matching between the high pressure compressor (HPC) and the high pressure turbine (HPT) is achieved by the ShaftPort connection and the HP_Shaft element. Likewise, the fuel supplied to the burner is achieved by the FuelIn element and the FuelPort connection between the two elements. The PERF element contains the engine performance parameters such as thrust, net thrust, ram drag, etc.

The NPSS environment is essentially textfile-based. The text is broken down into three main categories; creation of objects, assignment of values to variables, and commands. The following list of files illustrates an example of those required for successful operation within NPSS:

1. turbojet.mdl—this file configures the engine and runs the simulation
2. turbojet_HPC.map—this file contains the compressor performance map
3. turbojet_HPT.map—this file contains the turbine performance map
4. turbojet.view_page—this file determines the format of the output
5. turbojet.output—this is the output file generated by running the simulation

The next section of the paper describes how the flow matching was achieved for a supersonic turbojet engine using an MHD energy bypass system.
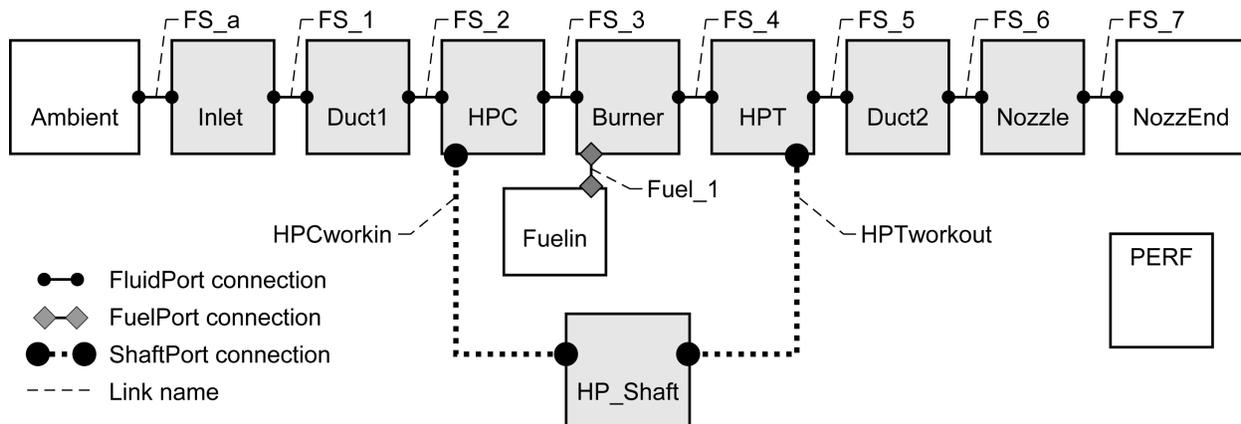
Figure 2.—Diagram of a NPSS turbine engine model. Reference flow stations and element names are indicated.

1-D Thermodynamic Equations for MHD Energy Bypass

The goal of this analysis is to achieve flow matching between the MHD energy bypass system and a supersonic turbojet engine and show that a supersonic turbojet engine can theoretically operate at all ambient Mach numbers between Mach 0 and Mach 7. In order to achieve this goal, the NPSS environment is chosen since it can model the thermodynamic cycle analysis of a turbojet engine. Also, since NPSS is object oriented and modular, additional components modeling the behavior of all the MHD components can be created within NPSS and wrapped around an existing NPSS supersonic turbojet engine. This analysis uses a supersonic turbojet engine model previously developed by Christopher Snyder (Ref. 6) (NASA Glenn Research Center) within the NPSS environment and uses a new NPSS object within that model called DuctMHD. The new NPSS object created by the author and Mr. Snyder is a computer code used for simulating the MHD energy bypass system; the pre-ionizers, the MHD generator and the MHD accelerator. The equations that are coded within the new NPSS object, DuctMHD are described below.

The enthalpy extraction ratio is determined by the output power produced by the MHD generator and the enthalpy input through the "inlet" of the MHD generator. The MHD generator extracts kinetic energy from the incoming flow ionized by the pre-ionizer positioned in front of the MHD generator. The calculation of this extracted kinetic energy, P_{elec}, is shown in the following equation derived by S.N.B. Murthy et al. (Ref. 7)

$$P_{\text{elec}} = \sigma v^2 B^2 K(1-K) A_g L \tag{1}$$

where the loading parameter, $K = 0.5$ for maximum power output in a Faraday generator. Thus, the enthalpy extraction ratio, $\eta_{N(g)}$, is calculated as follows:

$$\eta_{N(g)} = \frac{P_{\text{elec}}}{\dot{m} C_p T_{0,\text{entrance}}} = \frac{T_{0,12} - T_{0,14}}{T_{0,12}} \tag{2}$$

This value is the ratio of the extracted electrical energy and the enthalpy at the inlet of the MHD generator. Therefore, the stagnation (total) temperature at the exit of the pre-ionizer is modeled by adding a small portion of the extracted enthalpy back into the flow and is calculated as follows:

$$T_{0,\text{exit}} = \frac{T_{0,\text{entrance}}}{1 - \chi \eta_{N(g)}} \tag{3}$$

In the traditional manner, the stagnation pressure ratio of the pre-ionizers is calculated as shown here (Ref. 8) (Heiser, Eq. 2-114) which assumes a constant static pressure energy addition process.

$$\pi_p = \left[1 + \frac{\gamma - 1}{2} M_{\text{entrance}}^2 \left(1 - \frac{T_{0,\text{entrance}}}{T_{0,\text{exit}}} \right) \right]^{\gamma/1-\gamma} \tag{4}$$

The exit temperature of the MHD generator can also be computed using the enthalpy extraction ratio since energy is taken out of the flow.

$$T_{0,14} = T_{0,12} \left(1 - \eta_{N(g)} \right) \tag{5}$$

The stagnation pressure ratio for the MHD generator (Ref. 9) is

$$\pi_g = \left(1 - \frac{\eta_{N(g)}}{\eta_{s(g)}}\right)^{\frac{\gamma}{\gamma-1}} \tag{6}$$

where 90 percent isentropic efficiency ($\eta_{s(g)} = 0.9$) is assumed. Because the MHD generator extracts energy, the MHD accelerator takes that energy and uses it to add more energy to the flow. Hence, there is a temperature increase calculated as

$$T_{0,6} = T_{0,58} + \frac{P_{\text{elecA}}}{\dot{m}Cp} \tag{7}$$

where P_{elecA} is the energy used by the MHD accelerator that is bypassed from the MHD generator. The energy is a percentage of P_{elec} and is expressed as:

$$P_{\text{elecA}} = P_{\text{elec}}(1 - 2\chi) \tag{8}$$

where for this analysis, 10 percent of the power that is bypassed is used for both pre-ionizers ($\chi = 0.05$ or 5 percent of power is used for each). Thus, 90 percent of the electrical power extracted from the ionized flow at the MHD generator stage is transferred to the MHD accelerator. The stagnation pressure ratio for the MHD accelerator (Ref. 9) is expressed as

$$\pi_a = \left(1 + \eta_{N(a)}\eta_{s(a)}\right)^{\frac{\gamma}{\gamma-1}} \tag{9}$$

where the enthalpy addition ratio is the amount of heat added into the flow at the MHD accelerator and is calculated as follows:

$$\eta_{N(a)} = \frac{P_{\text{elecA}}}{\dot{m}C_pT_{0,58}} = \frac{T_{0,6} - T_{0,58}}{T_{0,58}} \tag{10}$$

MHD Energy Bypass Modeled Within the NPSS Environment

All of the above equations were coded up and are part of the new NPSS object class called DuctMHD. The equations are used to model the physics of the MHD components; the pre-ionizers, MHD generator and MHD accelerator. The new MHD objects within NPSS were tested in a standalone mode (without any other type of NPSS objects connected to them) to verify the expected operation of each MHD component. In addition, the provided supersonic turbojet engine model in the NPSS environment was studied and runs were made without the additional MHD energy bypass system to obtain a baseline of results. Four additional NPSS objects; the pre-ionizer before the MHD generator, the MHD generator, the pre-ionizer before the MHD accelerator and the MHD accelerator were then installed around the turbomachinery objects of the supersonic turbojet engine NPSS model.

The schematic of the NPSS objects for this new supersonic turbojet engine model is illustrated in Figure 3. Note that the pre-ionizer before the MHD generator is located after the exit stage of the inlet and the pre-ionizer/MHD generator combination is located before the high pressure compressor. Likewise, the pre-ionizer before the MHD accelerator is located after the low pressure turbine and the pre-ionizer/MHD accelerator combination is located before the nozzle of the new supersonic turbojet engine. This arrangement allows the pre-ionizer/MHD generator combination to condition the flow seen by the
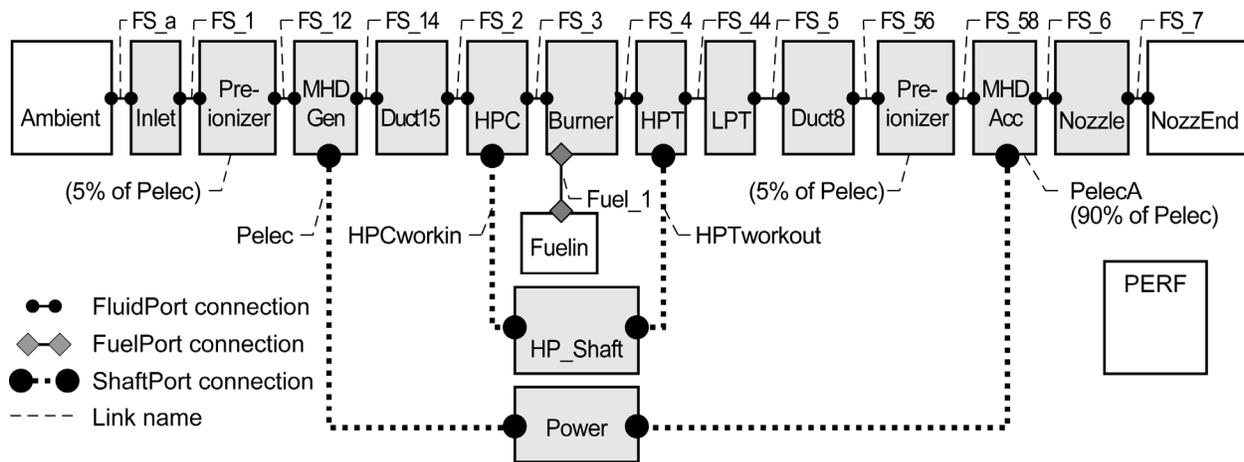
Figure 3.—MHD energy bypass system around a supersonic turbojet engine model within NPSS. Reference flow stations and element names are indicated.

fan/compressor stage of the engine and bypass the extracted energy to the pre-ionizer/MHD accelerator combination before the nozzle stage of the engine. In reality, there may be no need to dismantle the existing turbojet's nozzle and re-assemble it on the supersonic turbojet engine that has a MHD energy bypass system. However, an additional nozzle located at FS_6 in Figure 3 may be needed in addition to the new MHD components for this type of engine to be feasible.

In order to expand the operating range of a supersonic turbojet engine from a 0 to 3 Mach range to a 0 to 7 Mach range, the engine must be "tricked" into thinking it is flying at Mach 3 conditions. In order to do this, enough heat needs to be taken out of the flow before the fan stage (labeled FS_14 in Fig. 3). An iterative approach within NPSS, involving the exit total temperature of the MHD generator and conductivity levels, determined that with a 2 Tesla applied magnetic field and a MHD generator length of 3 m, an ionized flow of less than 10 mhos/m was needed to withdraw enough heat to allow the NPSS model to converge (i.e., successfully execute with no errors) at ambient Mach numbers above Mach 3. The analysis was driven by varying the conductivity of the ionized flow to get the desired temperature decrease at the compressor stage and resulted in an expanded operating range of 0 to 7 Mach. At higher Mach numbers, however, it was found that instead of lowering the total temperature at stage FS_14 all the way down to 600 K, it was lowered to a higher total temperature in order to successfully run the engine cycle.

MHD Energy Bypass Turbojet Cycle Flow Matching Results

An NPSS cycle analysis with the model depicted in Figure 3 was conducted in order to determine the basic geometry and electromagnetic conditions (length, flow area, applied magnetic field, and conductivity levels) required for the MHD components installed on a supersonic jet engine. It was also desired to demonstrate successful operation of this MHD energy bypass turbojet cycle on a full range of Mach numbers from Mach 0 to Mach 7. Both of these goals were met with this analysis.

The following operating parameters were studied that resulted from the NPSS cycle analysis.

1. Conductivity levels
2. Power extracted from ionized flow
3. Enthalpy extraction/addition ratios
4. Total and static pressures
5. Total and static temperatures
6. Gross thrust, net thrust, specific net thrust

The data of most interest will be presented here. The focus at present is on the specific net thrust of the resulting MHD turbojet compared to the original turbojet and the total pressures and total temperature profiles throughout the flow path of the supersonic turbojet engine with and without the MHD energy bypass system.

Conductivity Levels

Figure 4 shows the conductivity levels needed in order for the NPSS cycle analysis to fully operate between Mach 3.25 and Mach 7.0 for the MHD energy bypass components installed on a supersonic turbojet engine with an MHD generator length of 3 m. Multiple runs were made with a range of applied magnetic fields from 1 to 5 Tesla. However, at the 1 Tesla level, the conductivity levels are higher than reasonably practical with a top value of almost 35 mhos/m. Even at the 2 Tesla level, the highest conductivity level is almost 10 mhos/m. Figure 4 shows the conductivity levels for applied magnetic fields of 2.5 to 5 Tesla. Notice that the levels are kept under 5.5 mhos/m which is a reasonable maximum limit as indicated by previous research (Ref. 10).

Extracted Electrical Power

Figure 5 shows the actual amount of electrical power extracted from the ionized flow at the MHD generator stage of the supersonic turbojet engine with MHD energy bypass installed in megawatts of power. The amount of power extracted varies with ambient Mach number and has a range of 45 to 90 MW. In this model, 90 percent of the extracted electrical energy is used by the MHD accelerator and the pre-ionizers each use 5 percent of the extracted energy.
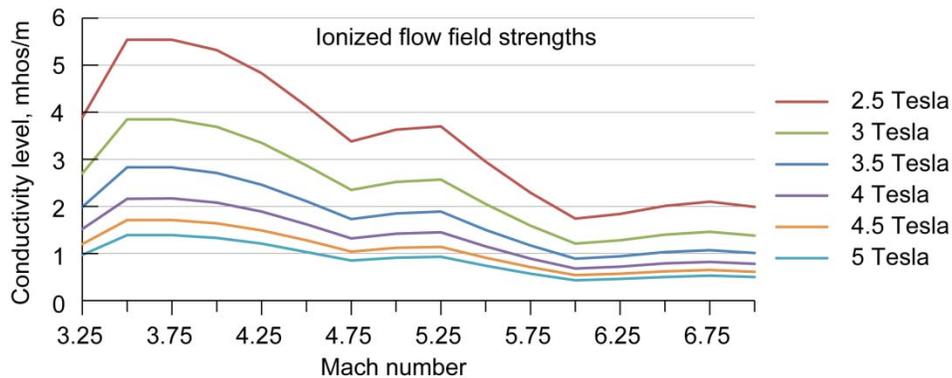
Figure 4.—Conductivity levels at ambient Mach number range of Mach 3.25 to Mach 7. MHD generator length of 3 m and a range of applied magnetic fields of 2.5 to 5 Tesla.
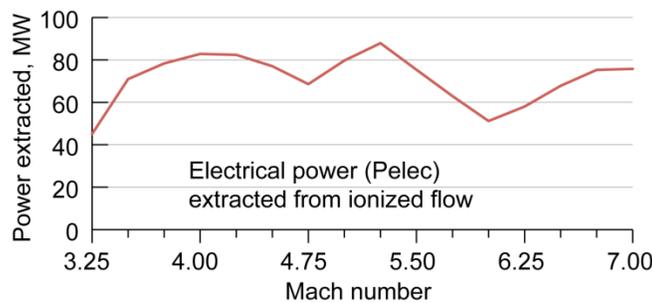
Figure 5.—Power extracted at ambient Mach 3.25 to Mach 7. MHD generator length of 3 m.

It is interesting to note that the amount of energy extracted varies widely particularly between ambient Mach = 4.75 and 7. Between ambient Mach = 4.75 and 5.25, the amount of power extracted (P_{elec}) increases linearly which is due to the fact that while $\dot{m}$ and $\eta_{N(g)}$ remain constant at ~10 kg/s and ~50 percent respectively, the value of $T_{0,12}$ increases from 1180 to 1380 K. On the other hand, P_{elec} decreases linearly from ambient Mach = 5.25 and 6.00 mainly because $\dot{m}$ decreases from ~10 to ~4 kg/s. From ambient Mach = 6.00 to 6.75, the value of P_{elec} increases again because in this region, $\dot{m}$ increases from ~4 to ~5 kg/s and $\eta_{N(g)}$ remain relatively constant at ~60 percent while $T_{0,12}$ increases from 1720 to 2089 K.

Enthalpy Extraction/Addition Ratios

The percent of the amount of electrical energy extracted out of the flow within the MHD generator is indicated in Figure 6 for each ambient Mach number in this MHD energy bypass study. The ratio is based on the amount of energy needed to be extracted to allow the supersonic turbojet engine to realize Mach 3 conditions for the engine's burner. Note that the percent extracted from the ionized flow varies between 10 and 60 percent. Figure 7 shows the enthalpy addition ratio of the MHD accelerator. Here, the ratios vary between 2 and 38 percent. It is interesting to note that both ratios generally increase as ambient Mach number increases.
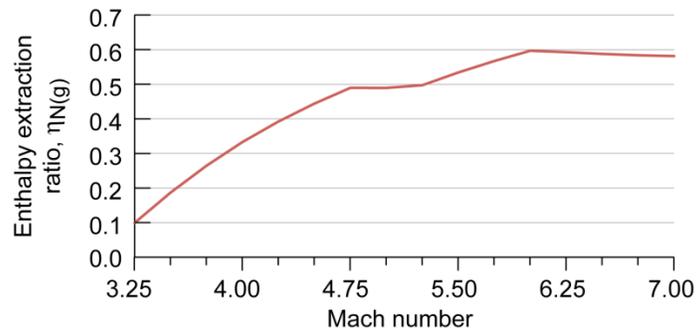
Figure 6.—Enthalpy extraction ratio at ambient Mach 3.25 to Mach 7. MHD generator length of 3 m.
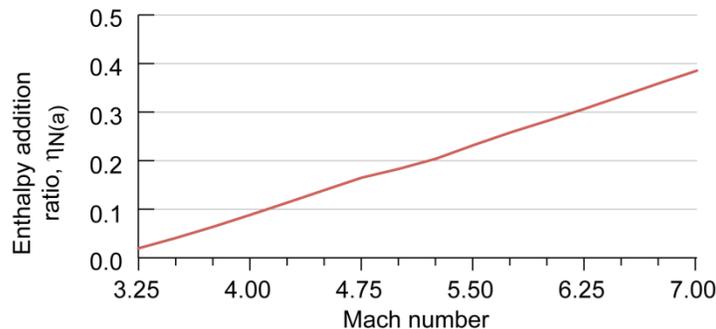
Figure 7.—Enthalpy addition ratio at ambient Mach 3.25 to Mach 7.

Total Temperature

Figures 8 and 9 show the total temperatures at each flow station in the supersonic turbojet model. Figure 8 shows the results of the runs without the MHD generator and MHD accelerator. The NPSS model does not run to convergence after reaching an ambient Mach of 3.75. Hence, only runs of ambient Mach 3 to Mach 3.75 are shown. Notice that until flow station FS_2 (exit stage of the duct before the high pressure compressor), the temperature stays fairly constant and from flow station number FS_2 to FS_4, there is a large increase in total temperature. These flow stations are located between the compressor and the high pressure turbine. This of course is to be expected as the turbojet's burner exit is located at station FS_4. The main objective here is to show the performance of the supersonic turbojet engine without MHD energy bypass and to achieve the same or nearly the same performance at higher Mach numbers with MHD energy bypass.
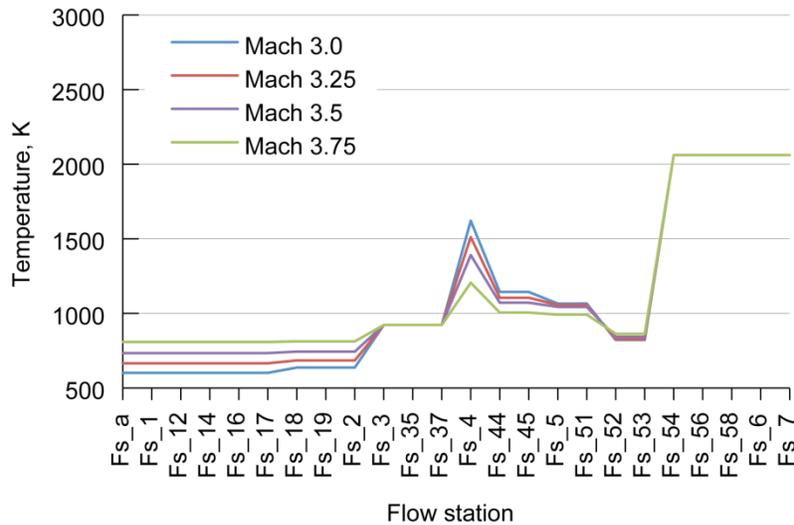
Figure 8.—Total temperature from entrance to exit. Performance shown without MHD energy bypass.
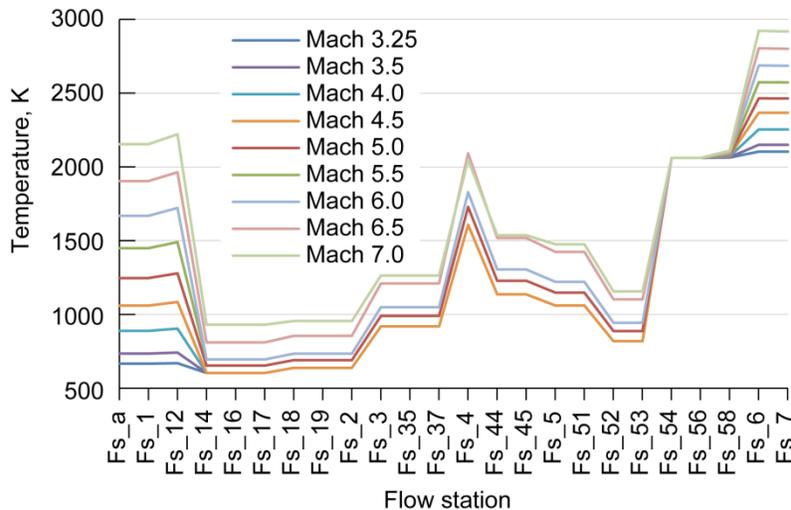
Figure 9.—Total temperature from entrance to exit. Performance shown with MHD energy bypass.

Figure 9 shows the total temperature from the inlet to the exit of the nozzle of the supersonic jet engine model with MHD energy bypass. Notice that there is a temperature decrease from station Fs_12 to Fs_14 on all cases. These stations are located before and after the MHD generator. This is also to be expected since the MHD generator works to draw out energy from the weakly ionized flow and thus lowers the temperature. Not all cases were able to decrease the total temperature at FS_14 (MHD generator exit) to the desired value of 600 K. This value of total temperature is what is achieved for the ambient Mach = 3.0 instance without MHD energy bypass and is considered the design point of the engine. At higher ambient Mach numbers (Mach 5 and greater), a higher total temperature at FS_14 is needed in order to have the engine cycle run successfully and produce positive specific thrust. These total temperatures ranged from 650 K (Mach 5) to 930 K (Mach 7). In addition, the total temperature increases from flow station FS_56 to FS_6 where the MHD accelerator is located. The energy bypassed from the MHD generator shows up as a total temperature increase at the MHD accelerator. Overall, the results in Figure 9 are very similar to those in Figure 8 with the exception of the ambient stage (FS_a) and the MHD accelerator nozzle stage (FS_6 and FS_7). These results mean that the MHD energy bypass is an effective tool for enabling a supersonic jet engine to fly at higher Mach numbers (from Mach 3.25 to Mach 7.0).

Total Pressure

Figures 10 and 11 show the total pressures at each flow station in the supersonic turbojet model. Figure 10 shows the results of the runs from Mach 3 to Mach 3.75 without the MHD energy bypass system. These are the highest ambient Mach number cases that run to convergence. As expected, the increase in total pressure happens through the high pressure compressor (FS_2) with peak pressure at FS_3 and the total pressure decreases through the turbine (FS_5).
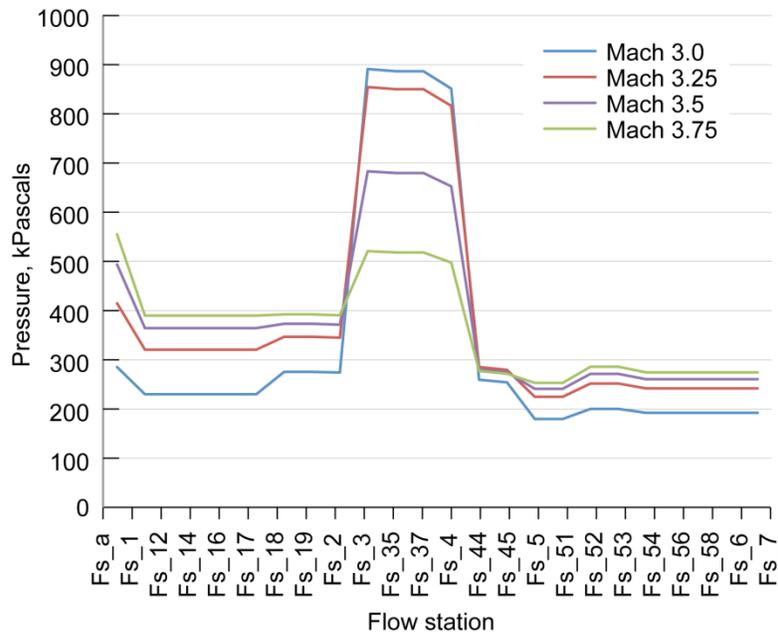
Figure 10.—Total pressure from entrance to exit. Performance shown without MHD energy bypass.
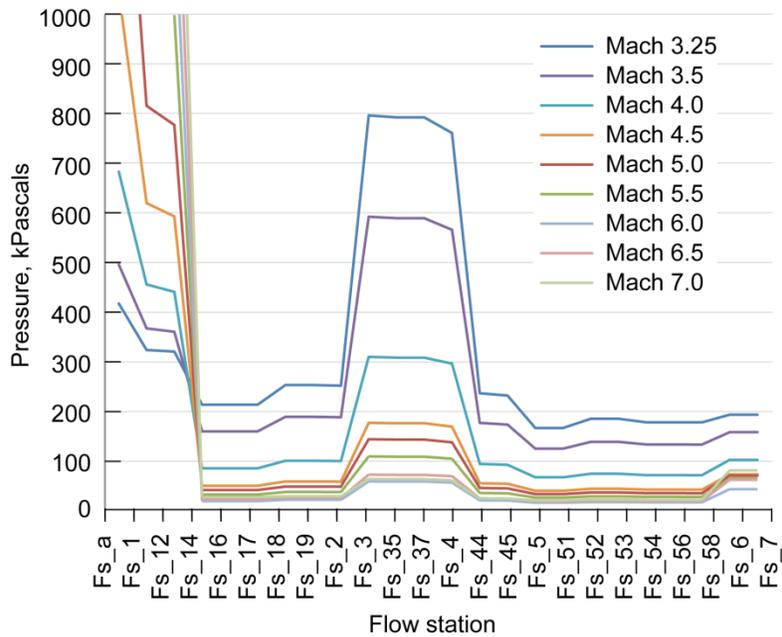
Figure 11.—Total pressure from entrance to exit. Performance shown with MHD energy bypass.

Comparing this to Figure 11, one can see that the total pressure is somewhat suppressed from FS_2 to FS_5 on cases Mach 3.5 and above as compared to the case operating without MHD. This suppression is due to the MHD energy bypass system and the result of extracting out a rather substantial amount of energy from the ionized flow. At the higher ambient Mach numbers (greater than Mach 4.0), the total pressure losses are particularly high. This is due to the fact that more kinetic energy is extracted out (40 to 60 percent) of the flow through the MHD generator in order to lower the total temperatures as compared to the lower ambient Mach numbers (Mach 3.25 to Mach 4.00) where 10 to 35 percent of the kinetic energy is extracted out of the ionized flow. Notice as well, that at ambient Mach numbers equal to and greater than 5.5, the total pressures at the burner are below that at sea level (101 kPa) and at this condition, the turbojet engine would require a special burner design to keep the burner lit and operating efficiently. However, the overall shape of the total pressure data from inlet to nozzle remains similar to the cases without MHD energy bypass suggesting that the supersonic turbojet engine with MHD energy bypass operates at the higher Mach numbers as it would at the lower Mach numbers without MHD energy bypass.

Specific Net Thrust

And finally, the specific net thrust of the supersonic turbojet engine with MHD energy bypass is shown in Figure 12. Without MHD energy bypass, the turbojet model does not run to convergence (i.e., execute successfully) above Mach 3.75 and the results in Figure 12 show specific net thrust results without MHD energy bypass from Mach 0 to Mach 3.25 because that is the normal operating range of this supersonic engine. Notice that the specific net thrust decreases only slightly at Mach 3.25 with MHD energy bypass turned "on" and positive specific net thrust is realized for all Mach numbers to the desired upper limit of Mach 7. As mentioned in the total temperature results section, the data in Figure 12 is achieved by allowing the MHD generator exit temperatures (FS_14) to increase from 600 K to a range of 650 K (Mach 5) to 930 K (Mach 7). These specific net thrust results are comparable to previous research completed by the author (Ref. 11).
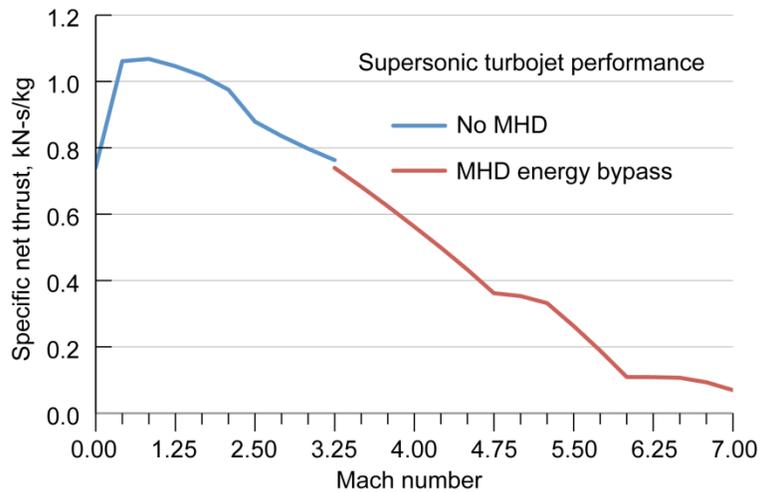
Figure 12.—Specific net thrust from Mach 0 to Mach 7. Performance shown with and without MHD energy bypass.

Conclusions

A supersonic turbojet engine with MHD energy bypass was modeled under the NPSS software environment. This software environment realistically models the physical interactions that take place throughout an aeropropulsion engine. The new NPSS element (DuctMHD) models the pre-ionizers, the MHD generator, and the MHD accelerator. Verifying the operation of DuctMHD was done with a test harness before installing the MHD components on a model of a supersonic turbojet engine. Normal operation for the supersonic turbojet model of this study is in the Mach 0 to Mach 3 range. The MHD components were "wrapped" around the supersonic turbojet model and runs were made without MHD energy bypass and with MHD energy bypass. The model ran from Mach 0 to Mach 3.75 without MHD energy bypass and ran from Mach 0 to Mach 7 with MHD energy bypass. The length of the MHD generator was kept at 3 m and a full range of applied magnetic field values from 1 to 5 Tesla were used to run the test cases. As a result, the case with an applied magnetic field of 2.5 Tesla offered a desired conductivity level range from 2 mhos/m to no more than 5.5 mhos/m. The range of electrical power extracted from the ionized flow of the MHD generator was found to be between 45 and 90 MW which translated to between 10 and 60 percent of the energy being extracted. The MHD accelerator used 90 percent of the extracted power which when added back, results in an enthalpy addition ratio, $\eta_{N(a)}$, between 2 and 38 percent back into the flow. The specific net thrust from these runs enabled positive values from 740 N-s/kg (at ambient Mach = 3.25) to 70 N-s/kg (at ambient Mach = 7).

Results from this study confirm that operating a supersonic turbojet in the Mach 0 to Mach 7 range is indeed possible provided that MHD energy bypass is installed on the engine. MHD technology can be a valuable addition to hypersonic flight in that it can expand the operating conditions of existing turbojet engines such as the supersonic turbojet engine studied in this analysis. This cycle analysis helps establish the operating conditions for a jet engine cycle that are optimal for kinetic energy transfer from inlet air to a downstream location in the engine. Further study will need to be done in order to determine a cost benefit ratio for MHD energy bypass as well as in sizing an engine with MHD energy bypass to the vehicle requirements to determine its feasibility in meeting the thrust requirements.

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14. ABSTRACT
Flow matching has been successfully achieved for an MHD energy bypass system on a supersonic turbojet engine. The Numerical Propulsion System Simulation (NPSS) environment helped perform a thermodynamic cycle analysis to properly match the flows from an inlet employing a MHD energy bypass system (consisting of an MHD generator and MHD accelerator) on a supersonic turbojet engine. Working with various operating conditions (such as the applied magnetic field, MHD generator length and flow conductivity), interfacing studies were conducted between the MHD generator, the turbojet engine, and the MHD accelerator. This paper briefly describes the NPSS environment used in this analysis. This paper further describes the analysis of a supersonic turbojet engine with an MHD generator/accelerator energy bypass system. Results from this study have shown that using MHD energy bypass in the flow path of a supersonic turbojet engine increases the useful Mach number operating range from 0 to 3.0 Mach (not using MHD) to a range of 0 to 7.0 Mach with specific net thrust range of 740 N-s/kg (at ambient Mach = 3.25) to 70 N-s/kg (at ambient Mach = 7). These results were achieved with an applied magnetic field of 2.5 Tesla and conductivity levels in a range from 2 mhos/m (ambient Mach = 7) to 5.5 mhos/m (ambient Mach = 3.5) for an MHD generator length of 3 m.

15. SUBJECT TERMS
Magnetohydrodynamic simulation; Thermodynamics; Jet thrust; Supersonic turbojet

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