Thermodynamic Cycle Analysis of Magnetohydrodynamic-Bypass Hypersonic Airbreathing Engines

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Nomenclature

C_p	=	constant pressure specific heat
F	=	thrust
f	=	fuel-to-air mass flow ratio
h	=	enthalpy
M	=	Mach number
$\dot{m}$	=	mass flow rate
p	=	pressure
q_f	=	fuel heating value
T	=	temperature
u	=	velocity
γ	=	specific heat ratio
Δ	=	difference
η_c	=	combustion efficiency
η_N	=	enthalpy extraction/addition ratio
η_s	=	isentropic efficiency
Π	=	global stagnation pressure ratio
π	=	stagnation pressure ratio
χ	=	ionizer power fraction

Subscripts

a	=	ambient air or accelerator
actual	=	actual process
b	=	burner
d	=	diffuser
e	=	cooling expansion
f	=	fuel
g	=	generator
isentropic	=	isentropic process
lim	=	limiting condition
n	=	nozzle
p	=	preionizer
0	=	stagnation condition

Introduction

ESTABLISHED analyses of conventional ramjet/scramjet performance characteristics indicate that a considerable decrease in efficiency can be expected at off-design flight conditions. This can be explained, in large part, by the deterioration of intake mass flow and limited inlet compression at low flight speeds and by the onset of thrust degradation effects associated with increased burner entry temperature at high flight speeds. In combination, these effects tend to impose lower and upper Mach number limits for practical flight. It has been noted, however, that magnetohydrodynamic (MHD) energy management techniques represent a possible means for extending the flight Mach number envelope of conventional engines.[1–3] By transferring enthalpy between different stages of the engine cycle, it appears that the onset of thrust degradation may be delayed to higher flight speeds. Obviously, the introduction of additional process inefficiencies is inevitable with this approach, but it is believed that these losses are more than compensated through optimization of the combustion process.

The fundamental idea is to use MHD energy conversion processes to extract and bypass a portion of the intake kinetic energy around the burner. We refer to this general class of propulsion system as an MHD-bypass engine. In its generic configuration, an MHD generator is placed between the inlet and the burner as a means of converting flow kinetic energy into electrical power. In this way, the overall static temperature rise associated with inlet flow deceleration can be actively constrained, and the propulsion system is able to reach a higher freestream Mach number, that is, higher inlet stagnation enthalpy, before the burner entry temperature exceeds the design limit. Furthermore, given a fixed limit for burner entry temperature, the inlet MHD generator can decelerate the flow to a lower velocity than that attainable using a simple adiabatic compression process. Thus, it is possible to increase the freestream Mach number for which the flow remains subsonic throughout the burner, and the ramjet mode can be sustained to much higher flight Mach numbers.

In this scheme, the inlet air must be ionized and have high electrical conductivity to attain effective MHD interaction in the generator. At moderate hypersonic Mach numbers, for example, 12–18, it is possible to obtain the required levels of conductivity through equilibrium ionization of seeded air. At low hypersonic Mach numbers, for example, 5–12, however, it is necessary to divert a fraction of the bypassed power for operation of a nonequilibrium preionizer. Therefore, inlet air ionization is a key technical issue with respect to practical viability.

Although the MHD-bypass engine concept is of considerable contemporary interest to the hypersonics community, a review of the open literature has revealed only a small number of analytical investigations aimed at performance prediction of these systems.[4–9] These analyses have demonstrated favorable performance characteristics under highly specific flight conditions, but a simplified thermodynamic cycle analysis would also be useful for the purpose of assessing systems performance potential on a more generalized basis.

This Note provides a brief description of a recently reported analysis assessing the performance potential and scientific feasibility of MHD-bypass hypersonic airbreathing engines using fundamental thermodynamic principles.[10] The cycle analysis, based on a thermally and calorically perfect gas, incorporates strategically placed MHD devices in the flow path and accounts for aerodynamic losses and thermodynamic process efficiencies in the various engine components. MHD device performance is completely described in terms of an enthalpy extraction/addition parameter and an isentropic efficiency. A provision is also made for diverting a fraction of the bypassed electrical power to an air preionizer located at the inlet of the diffuser. The power consumed by the preionizer is considered only as a variable parameter. The detailed ionization kinetics are not addressed in this Note. The analysis, although certainly not applicable to detailed performance analysis, is fundamental and is suitable as an indicator of potential performance gains associated with MHD energy bypass. It also reveals the flight Mach number range over which the system can effectively operate and suggests the range of component efficiencies needed for successful implementation.

The prime technical objective was to find simple closed-form solutions for the performance of MHD-bypass airbreathing engines and use them to expose important trends and sensitivities, as well as to establish thermodynamic feasibility, without recourse to elaborate thermochemical calculations. From this standpoint,

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our methodology adheres to the analysis philosophy and spirit of Builder's pioneering approach.[11]

Thermodynamic Cycle Analysis

Cycle Description

We consider the thermodynamic cycle of a hypersonic airbreathing engine of the ramjet/scramjet class that is augmented with an MHD energy management system. The geometrical configuration investigated here follows the generic MHD-bypass engine concept. The various engine components are shown in Fig. 1a along with selected reference stations at critical axial positions along the engine flowpath. Figure 1b includes the entropy–enthalpy diagram for a modified Brayton cycle as represented by a sequence of eight process trajectories.

These process trajectories may be summarized as follows: ($a \rightarrow 1$) air preionization and heat addition, ($1 \rightarrow 2$) adiabatic compression and flow deceleration, ($2 \rightarrow 3$) MHD conversion of total enthalpy to electrical power and deceleration of the flow, ($3 \rightarrow 4$) constant static pressure and frictionless heat addition, ($4 \rightarrow 5$) adiabatic expansion to prevent the temperature from exceeding design limits in the accelerator, ($5 \rightarrow 6$) MHD conversion of electrical power to total flow enthalpy and acceleration of the flow, and ($6 \rightarrow 10$) adiabatic expansion and acceleration of the exhaust flow.

Thermal Design Constraints

Presently, materials used to construct the walls of combustion chambers and nozzles cannot tolerate temperatures much above 1200 K. Unlike gas turbine engines, however, the surfaces of ramjet/scramjet combustors can be kept much cooler than the main fluid stream by providing a shielding layer of relatively cool air near the wall. Therefore, this class of engine can accept higher peak burner temperatures and can operate at higher flight Mach numbers. In this way, the relative performance and operating range of ramjet/scramjet engines is greatly improved and extended over the gas turbine engine. As the flight Mach number continues to increase, however, the combustor inlet temperature also increases until, at some limiting Mach number, the peak cycle temperature begins to approach the temperature limit set by the wall materials and cooling methods. Because the heat energy added by fuel combustion can generate unacceptable temperature levels at the burner exit, we introduce a temperature design constraint on the peak combustor stagnation temperature in the form

$$T_{0,4} \leq T_{0,\text{lim}} \tag{1}$$

Because the stagnation temperature is always increased in the MHD accelerator and because this device will be subject to similar thermal design limits as the burner, it is possible to introduce an additional design constraint on the peak accelerator temperature in the form

$$T_{0,6} \leq T_{0,\text{lim}} \tag{2}$$

Even if material temperature limits could be extended, the static temperature at the burner entrance cannot be increased indefinitely. At temperatures approaching 2000 K, energy losses due to unequilibrated dissociation begin to impair performance and eventually overwhelm any benefits associated with increased cycle temperature. Based on the well-known thermodynamic characteristics of air, the maximum allowable burner entry temperature is normally found to fall in the range 1400–1700 K (Ref. 12). Therefore, a typical value for design is near 1600 K. For analysis purposes, we impose this practical thermodynamic constraint on the design by requiring that the static temperature at the burner entrance not exceed a specified limiting value:

$$T_3 \leq T_{3,\text{lim}} \tag{3}$$

This limiting value should be low enough that air may be approximated as a thermally perfect gas with no dissociation effects during the entire inlet conditioning process.

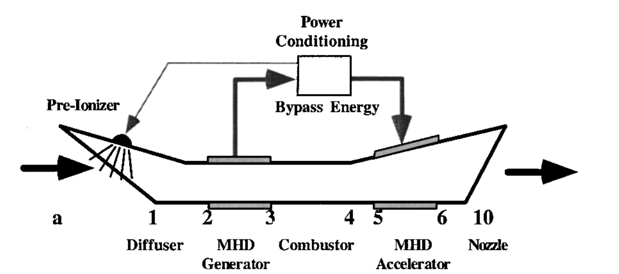

Fig. 1a Generic configuration of an airbreathing hypersonic engine with MHD energy management system; reference stations and process terminology are indicated.

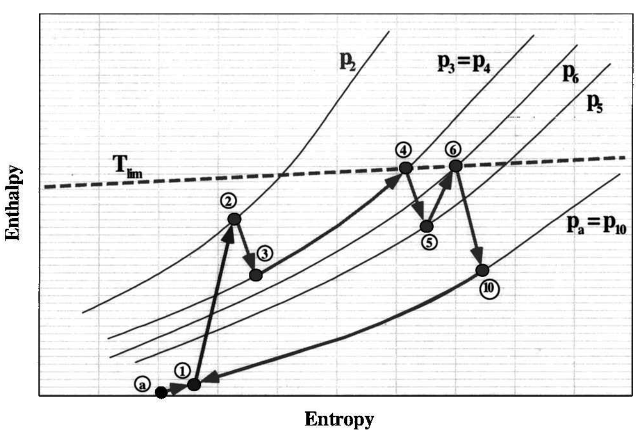

Fig. 1b Enthalpy–entropy process diagram for the cycle.

Basic Definitions

To simplify the analysis, we assume that the working medium can be treated as a pure substance throughout the engine flow path and that the working medium is thermally and calorically perfect. Because practical aerodynamic (nonisentropic) losses can lead to significant entropy increases and stagnation pressure losses along the flow path, it is necessary to introduce various process efficiencies into the analysis. These efficiencies are introduced in terms of a stagnation pressure ratio ($\pi = p_{0,\text{exit}}/p_{0,\text{in}}$) for each engine process. Under these assumptions, it is possible to develop relations describing the thermodynamic process trajectories in each component of the engine and to reach a simple closed-form solution for specific impulse I_{sp} and thrust specific fuel consumption (TSFC).

The objective of the analysis is to track the variation in stagnation properties through the various engine components using the first and second laws of thermodynamics. Before proceeding, it is useful to note that any MHD device can be described in terms of two fundamental thermodynamic parameters: 1) an enthalpy extraction/addition ratio η_N and 2) an isentropic efficiency η_s, which accounts for aerodynamic losses as well as joule dissipation effects. The enthalpy extraction/addition ratio is defined as the ratio of the stagnation enthalpy change in the device to the entrance stagnation enthalpy,

$$\eta_N = \Delta h_0 / h_{0,\text{ent}} \tag{4}$$

The isentropic efficiency represents the degree to which the actual process approaches an isentropic process. For a generator (energy extraction), it is defined as the ratio of the actual change in stagnation enthalpy to the ideal (isentropic) change in stagnation enthalpy that would accompany the same change in pressure,

$$\eta_{s(g)} = \frac{\Delta h_{0,\text{actual}}}{\Delta h_{0,\text{isentropic}}} \tag{5}$$

For an accelerator (energy insertion), it is defined as the ratio of the ideal to the actual,

$$\eta_{s(a)} = \frac{\Delta h_{0,\text{isentropic}}}{\Delta h_{0,\text{actual}}} \tag{6}$$

Note that the enthalpy extraction ratio and isentropic efficiency performance parameters fully define the operational characteristics of the generator and accelerator, including joule dissipation losses. Representative values can be specified based on historical data from past MHD research.

First and Second Law Considerations

Given the freestream stagnation enthalpy, it is possible to deduce the stagnation enthalpy at the various reference stations along the engine flow path. A summary of the results are as follows[10]:

$$T_{0,1} = \frac{T_{0,a}}{1 - \chi\eta_{N(g)}} \tag{7}$$

$$T_{0,2} = T_{0,1} \tag{8}$$

$$T_{0,3} = T_{0,2}\left(1 - \eta_{N(g)}\right) = T_{0,a}\frac{1 - \eta_{N(g)}}{1 - \chi\eta_{N(g)}} \tag{9}$$

$$T_{0,4} = \frac{T_{0,3} + (\eta_c f q_f / C_p)}{1 + f} \le T_{0,\mathrm{lim}} \tag{10}$$

$$T_{0,5} = T_{0,4} \tag{11}$$

$$T_{0,6} = T_{0,4} + \left(\frac{1}{1+f}\right)\frac{(1-\chi)\eta_{N(g)}}{1 - \chi\eta_{N(g)}}T_{0,a} \tag{12}$$

$$T_{0,10} = T_{0,6} \tag{13}$$

As the propellant flows through the engine, irreversibilities result in an increase in entropy and a reduction in stagnation pressure. Therefore, real aerodynamic losses (or gains) may be accounted for through the introduction of a stagnation pressure ratio ($\pi = p_{0,\mathrm{exit}}/p_{0,\mathrm{in}}$) for each engine process. Expressions for these π parameters can be developed from fundamental thermodynamic and gasdynamic principles as demonstrated for conventional engine components by Heiser and Pratt[12] and for MHD devices by Litchford et al.[10] Because the π parameters for the MHD devices in the engine flow path introduce novel considerations, we summarize the resulting relationships for these components as follows[10]:

$$\pi_g = \frac{p_{0,3}}{p_{0,2}} = \left[1 - \left(\frac{\eta_{N(g)}}{\eta_{s(g)}}\right)\right]^{\gamma/(\gamma-1)} \tag{14}$$

$$\pi_a = \frac{p_{0,6}}{p_{0,5}} = \left(1 + \eta_{N(a)}\eta_{s(a)}\right)^{\gamma/(\gamma-1)}$$

$$= \left[1 + \eta_{s(a)}\left(\frac{1}{1+f}\right)\frac{(1-\chi)\eta_{N(g)}}{1-\chi\eta_{N(g)}}\frac{T_{0,a}}{T_{0,4}}\right]^{\gamma/(\gamma-1)} \tag{15}$$

System Thrust Characteristics

The specific thrust of the MHD-bypass engine, including the effect of aerodynamic losses, can be readily determined by coupling the first and second law results with elementary gasdynamic relationships. Although the π parameters are not truly constant over large Mach number variations and γ can vary significantly through the engine flow path, the resulting closed-form solution demonstrates the essential performance characteristics of MHD-bypass airbreathing engines. In this case, the specific thrust takes the form[10]

$$\frac{F}{\dot{m}_a} = \left[(1+f)\sqrt{\frac{2\gamma R T_{0,6}(\Pi - 1)}{(\gamma-1)\Pi}} - M_a\sqrt{\gamma R T_a}\right]$$

$$+ \frac{p_e A_e}{\dot{m}_a}\left(1 - \frac{p_a}{p_e}\right) \tag{16}$$

where $T_{0,6}$ is obtained from Eq. (12) using $T_{0,4}$, that is, $T_{0,\mathrm{lim}}$, as a parameter and Π is a global stagnation pressure ratio having the form[10]

$$\Pi = \left\{1 + [(\gamma-1)/2]M_a^2\right\}[\pi_p\pi_d\pi_g\pi_b\pi_e\pi_a\pi_n(p_a/p_e)]^{(\gamma-1)/\gamma} \tag{17}$$

The fuel specific impulse and TSFC may be easily deduced from these results.

Subsonic Combustion Mach Number Constraint

The limitation on burner entry temperature leads directly to a restriction on the burner entry Mach number M_3. That is, the flow can be decelerated only a limited amount before the static temperature at the burner inlet becomes too great for effective combustion, and at some particular flight Mach number, it becomes necessary to transition to a supersonic combustion mode ($M_3 > 1$). For the MHD-bypass engine configuration, however, the burner entry temperature is affected by the enthalpy extraction process in the MHD generator. Indeed, the bypassing of flow enthalpy around the burner enables the vehicle to obtain a higher flight Mach number while maintaining a subsonic combustion mode. Given a specified $T_{3,\mathrm{lim}}$, it can be shown that the limiting flight Mach number for subsonic burner operation is given by the following relationship[10]:

$$M_a < \sqrt{\frac{2}{\gamma-1}\left[\left(\frac{\gamma+1}{2}\right)\frac{T_{3,\mathrm{lim}}}{T_a}\frac{1-\chi\eta_{N(g)}}{1-\eta_{N(g)}} - 1\right]} \tag{18}$$

Representative Performance Calculations

It is instructive to compare the performance of an MHD-bypass hypersonic airbreathing engine with that of a conventional ramjet system. For this purpose, Hill and Peterson's well-known analysis for a nonideal ramjet represents a suitable baseline case.[13] Indeed, their analytical results are directly recoverable from our development by simply eliminating all MHD interaction, that is, setting $\eta_{N(g)} = \eta_{N(a)} = 0$. Following Hill and Peterson, we assumed a freestream temperature of $T_a = 220$ K and used the thermodynamic properties of air throughout the engine flow path. The fuel heat of combustion was taken to be $q_f = 45 \times 10^3$ kJ/kg with 100% combustion efficiency, and a stagnation temperature limit was enforced at the burner exit. As in Hill and Peterson's case, we considered constant stagnation pressure ratios of $\pi_d = 0.7$, $\pi_b = 0.95$, and $\pi_n = 0.98$ for the diffuser, burner, and nozzle, respectively. As earlier noted, the calculations are limited because γ is not constant throughout the engine flowpath and because the stagnation pressure ratios are not independent of flight Mach number. These coefficients were taken as constants solely for the purpose of maintaining simplicity and clarity. We have optimistically assumed that $\eta_{s(g)} = \eta_{s(a)} = 0.9$ and computed π_g (loss) and π_a (gain) using Eqs. (14) and (15), respectively. The power needed to drive the preionizer is difficult to estimate at this juncture, and we utilized a value of $\chi = 0.05$ for demonstration purposes.

The computed specific thrust is shown as a function of flight Mach number in Fig. 2 for enthalpy extraction ratios of $\eta_{N(g)} = 0$, 0.25,

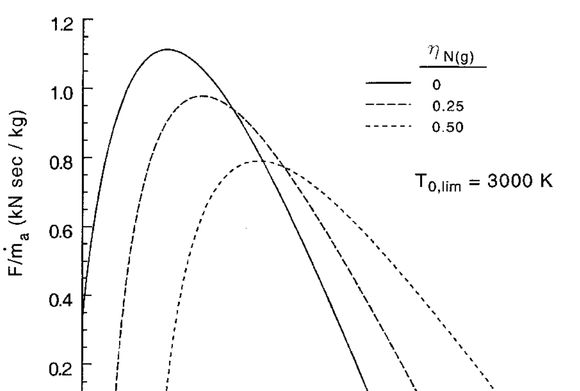

Fig. 2 Specific thrust characteristics as a function of flight Mach number for $\eta_{N(g)}$ = 0, 0.25 and 0.5 assuming $\eta_{s(g)} = \eta_{s(a)}$ = 0.9 and $T_{0,\mathrm{lim}}$ = 3000 K.

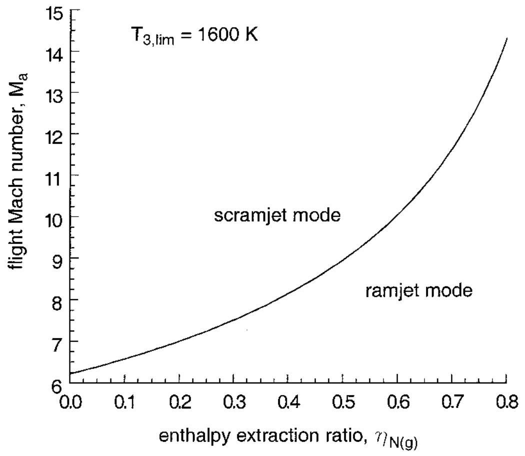

Fig. 3 Maximum flight Mach number for maintaining subsonic combustion conditions as a function of the generator enthalpy extraction ratio; assumes a maximum static burner entry temperature of $T_{3,\lim}$ = 1600 K.

and 0.5 and a maximum burner stagnation temperature of 3000 K. The case without any MHD interaction corresponds directly with Hill and Peterson's results[13] and is demonstrative of a conventional hypersonic airbreathing engine. The specific thrust in this instance peaks at a flight Mach number between 2 and 3 after which it steadily decreases to zero near $M_a = 8$. The results with MHD interaction demonstrate a reduction in peak performance and a shifting of the specific thrust curve to higher flight Mach numbers. The loss in performance using MHD-bypass is due to increased nonisentropic losses associated with the MHD energy conversion devices. However, the ability to bypass flow enthalpy around the burner permits optimization of the combustion process at higher flight Mach numbers and enables the production of thrust in a flight regime not obtainable with conventional engines. This capability is the primary advantage of the MHD-bypass concept.

The combustion optimization attributes can be better appreciated, perhaps, through an inspection of the maximum flight Mach number that can be achieved with MHD-bypass of flow enthalpy while maintaining subsonic combustion conditions. This effect, shown in Fig. 3, is demonstrated through solution of Eq. (18) assuming a maximum static burner entry temperature of $T_{3,\lim} = 1600$ K. This envelope indicates that the enthalpy extraction ratio in the generator must be extremely high to maintain ramjet mode operation, irrespective of the process efficiencies.

Conclusions

It has not escaped the authors' attention that our simplified thermodynamic cycle analysis is greatly limited by the assumption of constant stagnation pressure ratios for the various engine components; nevertheless, the analysis does reveal the essential operational benefits of MHD-bypass engines and demonstrates fundamental scientific feasibility. Clearly, bypassing energy around the burner extends the operational Mach number envelope of conventional airbreathing engines, but it is important to note that system performance is extremely sensitive to nonisentropic losses in the MHD devices and that any favorable operational characteristics will disappear if these losses become too large.

We conclude that MHD-bypass systems hold significant promise for extending the effective operating range of conventional hypersonic airbreathing engines and believe that the present results justify a more in-depth analysis in which the stagnation pressure ratios become dependent on flight Mach number, and the combustion process is modeled more accurately.

Acknowledgments

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References

[1] Novichokv, N., "Space Wings of Russia and the Ukraine," *Echo of the Planet/Aerospace*, Moscow, Sept. 1990.

[2] Gurijanov, E. P., and Harsha, P. T., "AJAX: New Directions in Hypersonic Technology," AIAA Paper 96-4609, 1996.

[3] Bityurin, V. A., Lineberry, J. T., Potebnia, V. G., Alferov, V. I., Kuranov, A. L., and Sheikin, E. G., "Assessment of Hypersonic MHD Concepts," AIAA Paper 97-2393, 1997.

[4] Bruno, C., Czysz, P. A., and Murthy, S. N. B., "Electro-Magnetic Interactions in Hypersonic Propulsion Systems," AIAA Paper 97-3389, 1997.

[5] Bruno, C., and Czysz, P. A., "An Electro-Magnetic-Chemical Hypersonic Propulsion System," AIAA Paper 98-1582, 1998.

[6] Brichkin, D. I., Kuranov, A. L., and Sheikin, E. G., "MHD Technology for Scramjet Control," AIAA Paper 98-1642, 1998.

[7] Kuranov, A. L., and Sheikin, E. G., "The Potential of MHD Control for Improving Scramjet Performance," AIAA Paper 99-3535, 1999.

[8] Park, C., Bogdanoff, D., and Mehta, U. B., "Theoretical Performance of Frictionless MHD-Bypass Scramjets," *Journal of Propulsion and Power* (to be published).

[9] Chase, R. L., Mehta, U. B., Bogdanoff, D. W., Park, C., Lawrence, S. L., Aftosmis, M. J., Macheret, S., and Shneider, M., "Comments on an MHD Energy Bypass Engine Powered Spaceliner," AIAA Paper 99-4975, 1999.

[10] Litchford, R. J., Cole, J. W., Bityurin, V. A., and Lineberry, J. T., "Thermodynamic Analysis of the AJAX Propulsion Concept," NASA TP-2000-210387, July 2000; also AIAA Paper 2000-0445, Jan. 2000.

[11] Builder, C. H., "On the Thermodynamic Spectrum of Airbreathing Propulsion," AIAA Paper 64-243, 1964.

[12] Heiser, W. H., Pratt, D. T., Daley, D. H., and Mehta, U. B., *Hypersonic Airbreathing Propulsion*, AIAA Education Series, AIAA, Washington, DC, 1994, pp. 1–512.

[13] Hill, P. G., and Peterson, C. R., *Mechanics and Thermodynamics of Propulsion*, 2nd ed., Addison–Wesley, Reading, MA, 1992, pp. 157–164.