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Power Requirement for Nonequilibrium MHD-Bypass Scramjet

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Summary

It has been suggested previously that the performance of scramjet propulsion system may be improved by the use of magnetohydrodynamic (MHD) energy bypass: an MHD generator could be made to decelerate the flow entering the combustor, thereby improving combustion efficiency, and the electrical power generated could be made to accelerate the flow exiting from the combustor prior to expanding through the nozzle. In one of such proposed schemes, the MHD generator is proposed to be operated at a low temperature and ionization is to be achieved under nonequilibrium by the application of an external power. In the present work, the required power of such an external source is calculated assuming a 100%-efficient nonequilibrium ionization scheme. The power required is that needed to prevent the degree of ionization from reaching equilibrium with the low gas temperature. The flow is seeded with potassium or cesium. Specific impulse is calculated with and without turbulent friction. The results show that, for typical intended flight conditions, the specific impulse obtained is substantially higher than that of a typical scramjet, but the required external power is several times that of the power generated in the MHD generator.

Introduction

In the so-called AJAX concept[1], the performance of scramjet propulsion system is proposed to be improved by the use of a magnetohydrodynamic (MHD) energy bypass scheme. In this scheme, an MHD generator will be made to decelerate the flow entering the combustor, thereby improving combustion efficiency. The electrical power generated will be expended in an MHD accelerator located after the combustor to accelerate the flow exiting from the combustor prior to expanding through the nozzle.

In Refs. 2 and 3, such an MHD-energy bypass scheme is achieved by operating both the MHD generator and the accelerator in a thermochemical equilibrium environment. Ionization required for operating the MHD generator is obtained by the shock-compression of the oncoming air flow by the inlet ramps. Air will be seeded with potassium or cesium to produce ionization at a temperature of about 3000 to 3500 K. In both generator and accelerator, static pressure is typically of the order of a few atmospheres in this scheme. The calculations show that the MHD-bypass scheme offers a possibility of improving the scramjet performance at relatively high flight speeds. The main drawback of this scheme is that the strong compression needed to produce ionization also produces a large drag and consequently a poor specific impulse.

There is a parallel concept to the above equilibrium concept in which the MHD generator will operate in a thermochemical nonequilibrium regime. In that nonequilibrium MHD-energy bypass concept, the MHD generator will be operated at a low temperature and pressure. Ionization is produced by the application of an external power source. An electron beam has been investigated as a possible power source.[4] However, neutron beam or a strong light beam may also be a possibility. Such an external source ionizes the gas species either through a collisional or a radiative process. The advantage of this scheme is that only a weak shock-compression is needed in the inlet ramp, which would produce only a small drag and consequently a high specific impulse.

An attempt has been made in Ref. 4 to estimate the power of such an external source required to achieve the goal. It was concluded that only a small amount of power is needed for the scheme. However, the estimate was made considering only the local phenomena, and did not consider how the MHD generator will perform and how the entire scramjet propulsion system will perform with such a scheme. It was not shown whether the condition for which only a small external power is needed would lead to a satisfactory operation of the MHD generator or the scramjet propulsion system.

It is the purpose of the present work to estimate the power requirement for the external power source for a system in which the MHD generator will function and the scramjet propulsion system will produce useful thrust. For this purpose, calculation is made of the entire flow path for the scramjet vehicle which is equipped with the nonequilibrium MHD-energy bypass scheme.

The assumptions made are that: (1) the flow is one-dimensional, (2) the MHD devices function perfectly according to the one-dimensional MHD theory, (3) no shock wave is formed inside the MHD generator under any circumstance, and (5) the scheme for producing the nonequilibrium ionization has a 100% efficiency. A finite-rate kinetic calculation is made for the nozzle expansion. Calculation is made with and without turbulent friction. The turbulent case was calculated assuming that transition occurs at the leading edge.

Method of Calculation

The two-dimensional bypass scramjet system under consideration is sketched in Fig. 1. The general features of such a system is described in Ref. 2.

The flow path in the present nonequilibrium MHD-energy bypass system is shown schematically in Fig. 2. As shown in the figure, the oncoming air flow is first compressed through four ramps. The compressed gas is first seeded with either potassium or cesium, and then enters the MHD generator. The gas temperature at that point is assumed to be low but still sufficiently high to vaporize the seed material. Inside the generator, an external power source injects energy in the lateral direction so as to produce ionization of the seed vapor. The strength of the ionizer is tailored, that is, it is made to vary along the flow direction so as to maintain a constant degree of ionization, at a level required for satisfactory operation of the MHD generator

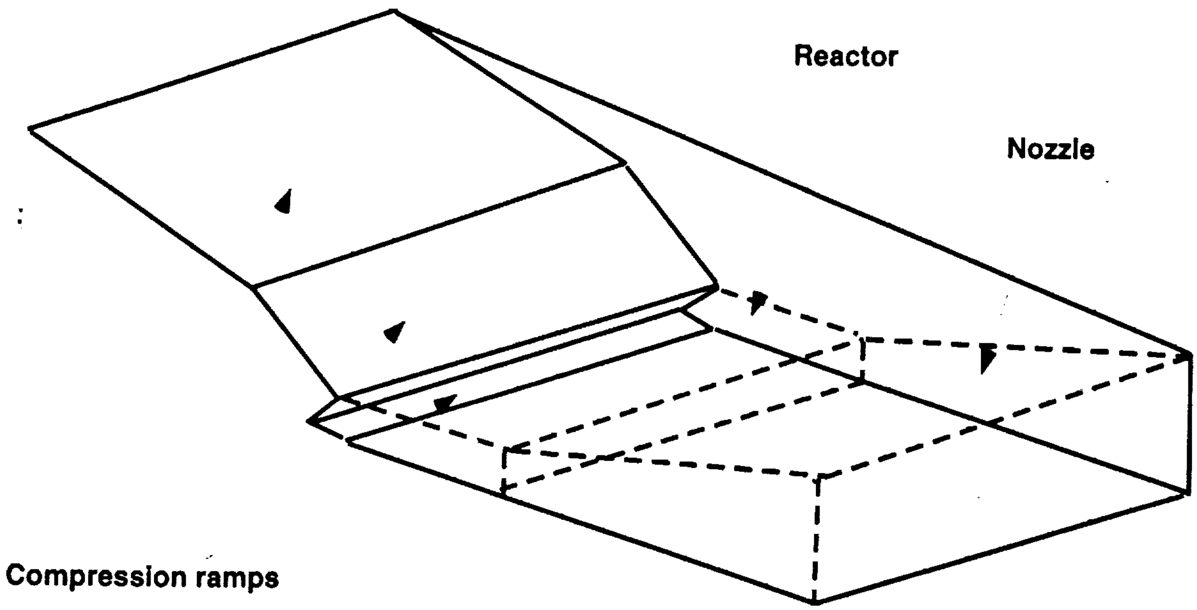

Figure 1. Sketch of the two-dimensional scramjet system.

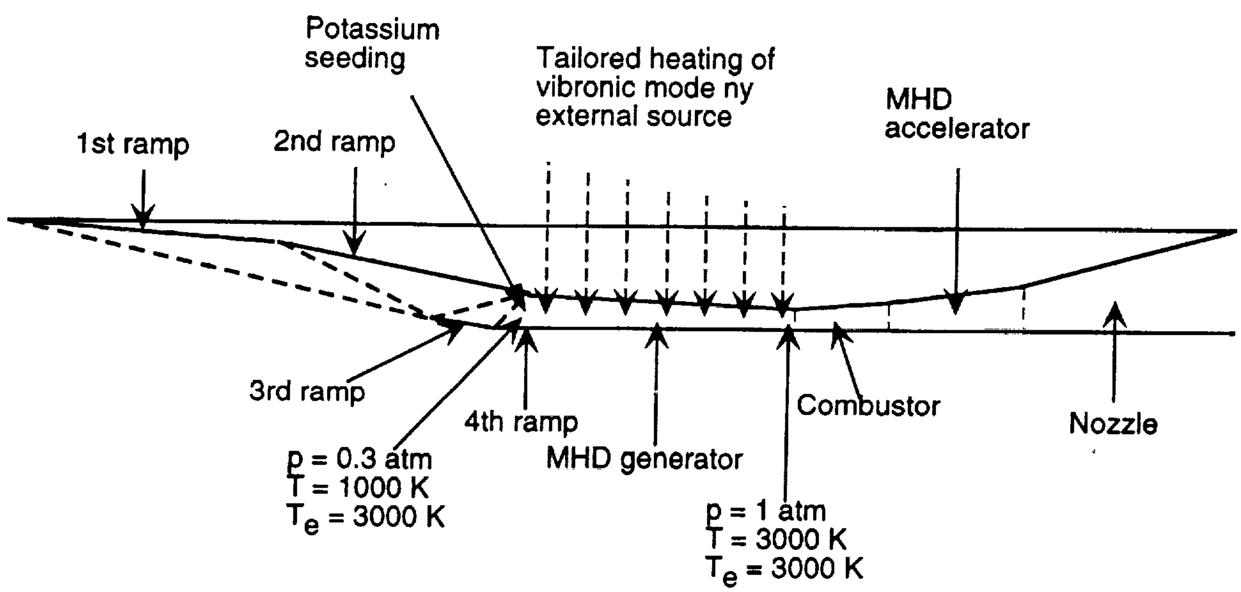

Figure 2. Schematic of the flow path.

How the ionizer functions is not specified in the present work. It is known that electron beam injected at small intervals across the MHD generator is satisfactory.[4] As mentioned, a neutron beam or a light source of specific wavelength could possibly be used in place of an electron beam. The ionizer is assumed to function with an efficiency of 100%. That is, the device producing the ionization is 100% efficient, and the delivered energy will not heat the translational mode of the cold gas.

The local strength of the ionizer required to maintain a constant degree of ionized is calculated through the following considerations. In order to ionize the seed species, an energy equal to the ionization energy of the seed species must be expended. Because, by assumption, the degree of ionization does not vary along the flow direction, there must be a thermochemical equilibrium between electron temperature and degree of ionization. However, because of the strong coupling of electron temperature and the vibrational mode of nitrogen molecules, vibrational model of nitrogen is excited to the electron temperature. Through vibration-vibration coupling between nitrogen and oxygen molecules, vibrational mode of oxygen molecules is also excited to the electron temperature. Thus, there develops a pool of energy, named here ionic-vibronic energy, which is the sum of (1) the chemical energy of ionization of the seed species, (2) the thermal energy of electrons, and (3) the vibrational energies of nitrogen and oxygen molecules. These three modes are in equilibrium among themselves in order to satisfy the condition of constant ionization.

E_v = Ionic-vibronic energy per unit volume
= ionization energy per unit volume
+ electron thermal energy per unit volume
+ vibrational energy of N_2 and O_2 per unit volume (1)

The ionic-vibronic energy is being bombarded by the collisions of the cold heavy gas. The rate by which the ionic-vibronic energy is depleted is:

R = Rate of cooling of E_v per unit volume
= that by T-to-T_e collisional thermalization
+ that by translational-vibrational energy transfer (2)

To oppose this cooling rate, an external power of intensity I, in the unit of power per unit volume, is being added, which is assmed to heat only to the ionic-vibronic energy E. The equation governing the process can be written as

$$dE_v/dt = I - R \quad (3)$$

The requirement that E_v remains constant reduces to

$$I = R \quad (4)$$

The constant-E_v condition is written as

$$E_v = \text{const.} \quad (5)$$

The total external power is given by

$$P = \int I dx \quad (6)$$

where x is the distance along the flow.

The system of differential equations governing MHD power generation[2,3] is integrated simultaneously with Eqs. (4) to (6). In doing so, the power factor E/(uB), where E, u, and B are transverse voltage gradient, axial flow velocity, and magnetic field strength, respectively, is kept at a specified constant value.

One major drawback of the nonequilibrium scheme is that the static pressure entering the combustor tends to be low. Such a low pressure will lead to a poor combustion and poor expansion ratio in the nozzle. There is a possibility of adjusting the cross-sectional area of the

MHD generator so as to raise static pressure along the axis. Generally, in a supersonic flow, such a measure leads to formation of a shock wave, and ensuing loss in the total pressure. However, whether shock will always form inside an MHD device is not well known. To seek the most optimistic prediction of the performance of the present scheme, the assumption is made, as mentioned in Introduction, that a slow compression in the MHD channel does not lead to shock formation.

When the flow exits from the MHD generator, the flow immediately reaches thermo-chemical equilibrium, because there is no longer the external source heating the ionic-vibronic mode. Therefore, the gas is assumed to be in thermochemical equilibrium in the combustor and the MHD accelerator. The gas expanding through the nozzle tends to undergo chemical freezing. This process is calculated by integrating the chemical rate equations.[2,3]

The skin friction inside the flow path is calculated using a well-known method.[3] The specific impulse of the entire system is calculated excluding or including the skin friction.

Results

In Table 1, a typical result of the calculation is presented. The case is where the combustor mach number is required to be below 1.2. The calculation shows that the specific impulse is large, but the external power required is many times that power generated by the MHD generator. The external power needed is about 85% of the hydrogen fuel expended, wherein the fuel energy is calculated assuming a complete combustion at a room temperature.

Table 1. Summary of a typical solution.

Flight speed = 2500 m/s

Flight dynamic pressure = 0.5 atm

Vehicle overall length = 36 m

Vehicle width = 1 m

Seed material = cesium

Conductivity in generator = 109 mho/m

Magnetic field for generator = 1.47 Tesla

Temperature at generator entrance = 1100 K

Pressure at generator entrance = 2.94×10^4 Pascal

Mach number at generator entrance = 2.17

Temperature at generator exit = 3320 K

Pressure at generator exit = 1.09×10^5 Pascal

Mach number at generator exit = 1.19

Ionizer power consumed = 8.27×10^8 W

Power generated = 1.51×10^8 W

H_2fuel flow rate = 7.18 kg/s

Post-combustion temperature = 3190 K

Post-combustion pressure = 8.84×10^4 Pascal

Magnetic field for accelerator = 2.83 Tesla

Mach number at accelerator entrance = 1.25

Mach number at accelerator exit = 1.58

Temperature at nozzle entrance = 3190 K

Pressure at nozzle entrance = 8.63×10^4 Pascal

Mach number at nozzle entrance = 1.42

Temperature at nozzle exit = 2190 K

Pressure at nozzle exit = 9.62×10^3 Pascal

Velocity at nozzle exit = 3267 m/s

Mach number at nozzle exit = 3.26

Skin friction = included

Thrust = 2.40×10^5 Newton

Specific impulse = 3295 sec

External power/(energy in fuel) = 0.85

The behavior of the heavy particle and the ionic-vibronic temperature and the expended external power in the generator are shown in Fig. 3. The five calculations made to date show results which are similar to the one shown. In the full paper, the results will be shown over a range of operating parameters.

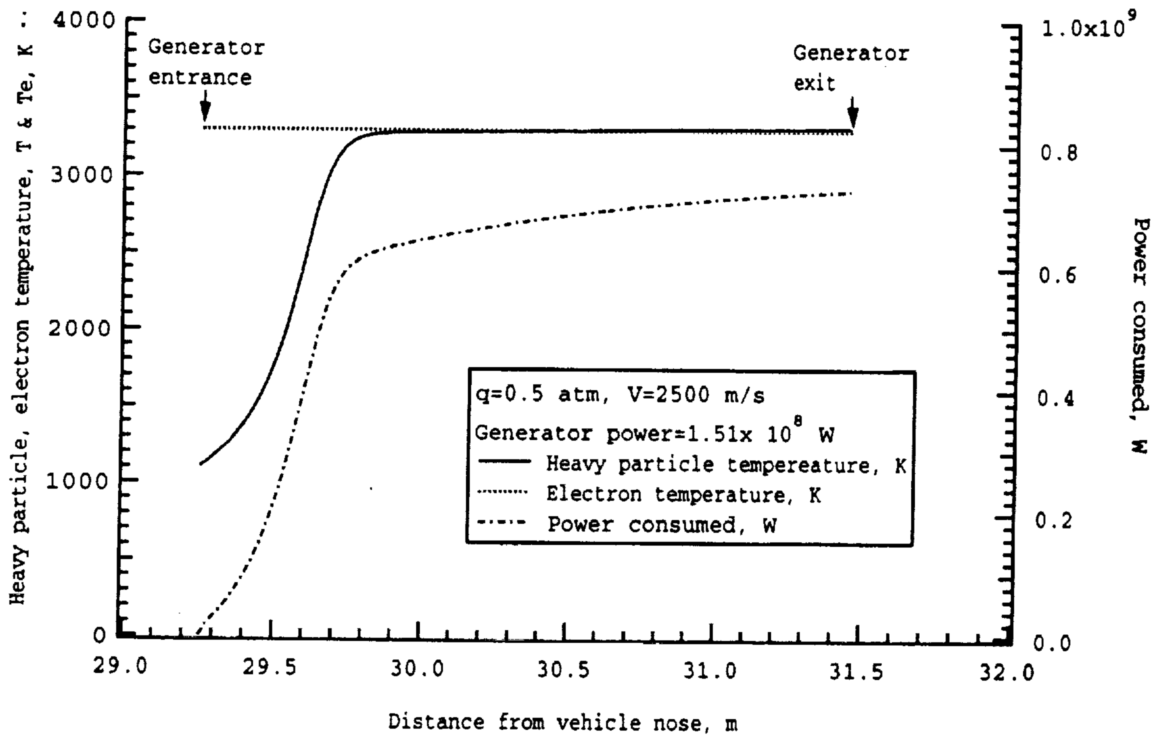

Figure 3. The behavior of the heavy particle and the ionic-vibronic (denoted as electron) temperature and the expended external power.

It is interesting to note that the vehicle described in Table 1 produces a finite thrust with no hydrogen fuel expended: it produces 5.3×10^4 Newton of thrust with zero fuel, which is about 22% of that given in Table 1. Similar calculation was made also to the case where degree of ionization is low, as envisioned in Ref. 4. The result shows that the MHD generator fails to decelerate the flow to the required low Mach number of 1.2 at the combustor entrance.

Conclusions

The MHD-energy bypass scramjet system operating on the nonequilibrium ionization will produce a large specific impulse. But, in order to maintain the necessary ionization level in the MHD generator, an external power source several times larger than the power generated is needed. This system will produce a significant thrust even without fuel. If operated at a very low degree of ionization, the MHD generator cannot decelerate the flow to the required low Mach number at the combustor entrance.

Acknowledgement

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