An Atomic Hydrogen Propulsion System

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Abstract

PERFORMANCE characteristics of a space propulsion system utilizing atomic hydrogen as a propellant are calculated. This thruster could be utilized for missions which require reliable long life operation, such as attitude correction, stationkeeping, and orbit change. A schematic diagram of the atomic hydrogen space propulsion thruster is shown in Fig. 1. An important feature of the engine is that atomic H is used as soon as it is produced by the discharge, thus eliminating the difficult problem of storage.[1,2] A mathematical model which describes the reaction chamber is presented; however, details of the microwave discharge, connecting regions, and other parts of the propulsion system are not discussed. The H_2 is assumed to be completely dissociated by the microwave discharge with no impurities. The mathematical model is formulated in terms of a derived set of coupled nonlinear, first-order, differential equations governing the rate of formation and collisional dissociation of H_2 and various energy loss mechanisms. These, in addition to the rate equation governing the density of atomic hydrogen in the chamber, are solved using iterative procedures. Based upon a specified flow rate of atomic hydrogen into the reaction chamber, values are given for the thrust, specific impulse, reaction chamber pressure and gas temperature, and the densities of H and H_2 inside the reaction chamber for a spherical reaction chamber geometry.

Contents

The objective of this work is to investigate the feasibility of producing an efficient rocket propulsion system with a specific impulse intermediate between that provided by electrostatic ion thrusters and conventional chemical propulsion systems. The propulsion system operates by flowing atomic hydrogen into a reaction chamber where recombination into molecular hydrogen takes place. The atomic hydrogen is produced by dissociating H_2 in a microwave discharge, which then flows via a pressure gradient out of the discharge region. Each recombination into H_2 releases 4.5 eV of energy which is used to heat the gas and produce thrust. However, not all this energy is available to heat the gas.

The dominant physical process that produces usable energy in the reaction chamber is the three-body recombination mechanism,

$$H + H + M \underset{k_M^{\mathrm{diss}}}{\overset{k_M^{\mathrm{rec}}}{\rightleftharpoons}} H_2 + M \tag{1}$$

which converts approximately 4.5 eV of chemical energy into the translational, vibrational, and rotational degrees of freedom of the reaction products. The recombination rate is given by k_M^{rec} and k_M^{diss} is the collisional dissociation rate constant.

In Eq. (1), M refers to species H, H_2, or some other buffer gas in the reaction chamber. Such three-body interactions comprise the volume recombination and dissociation processes. In addition to these processes, M may characterize the interaction with the surface, for which several distinct processes have been identified. The predominant surface recombination process appears to be first order in the gas phase density.

The rate of change of the density of H atoms inside the chamber is given by

$$\frac{dn_H^{\mathrm{in}}}{dt} = \frac{\xi_H}{V} - 2\frac{dn_{H_2}^{\mathrm{rec}}}{dt} + \frac{dn_{H_2}^{\mathrm{diss}}}{dt} - \frac{1}{V}\frac{dN_H^{\mathrm{ex}}}{dt} \tag{2}$$

where V is the volume of the reaction chamber and ξ_H is the number flow rate of atomic hydrogen in the reaction chamber. The second term in Eq. (2) is the rate at which H atoms are lost due to recombination, including surface recombination, and the third term is the rate H atoms are produced from thermal dissociation. The last term is the rate at which H atoms are exhausted from the chamber.

Initially most of the recombination energy resides in the vibrational and rotational states of the H_2 molecule,[3] although some energy is transferred to the translational kinetic energy of the reaction products.[4] Since only the translational kinetic energy can contribute to the reaction chamber pressure and the thrust via the expulsion of the reaction products out an exhaust port, it is important that much of the vibrational and rotational energy initially in the H_2 molecule be converted to translational energy. Potential energy of recombination is lost by escaping H atoms. In addition, energy is lost by reactive and nonreactive scattering of the reaction chamber constituents with the walls. The energy lost to the walls by surface recombination has been studied extensively by Melin and Madix[5] and Wise and Wood.[6] They have measured the recombination efficiency γ_H and the fraction of recombination energy β_H transmitted to the surface by surface recombination. The rate at which energy is lost to the surface due to surface recombination is proportional to the rate of surface recombination.[7] The constant of proportionality is the amount of energy lost per recombination event, $\beta_H E_r$. In this work interactions with the walls are treated in a simplified manner but it is apparent that these losses can, under some operating conditions, make major contributions to the thruster performance. A more comprehensive description of these mechanisms is in progress. The release of 4.5 eV per recombination and the energy losses mentioned above give a net translational kinetic energy available to heat the gas and produce usable thrust.

Assuming the translational, rotational, and vibrational degrees of freedom reach thermal equilibrium before being exhausted from the reaction chamber, the gas temperature $T(t)$ is calculated using the equipartition theorem. The thrust produced by the exhausting gases is determined by

$$F = \sum_i \frac{dN_i^{\mathrm{ex}}}{dt} v_i^{\mathrm{ex}} m_i \tag{3}$$

for gas species $i = H$, H_2, or M, where dN_i^{ex}/dt is the rate of exhaust of gas species i, v_i^{ex} the exhaust velocity of gas species i, and m_i the mass of gas species i.

Presented as Paper 82-1934 at the AIAA/JSASS/DGLR 16th International Electric Propulsion Conference, New Orleans, La., Nov. 17-19, 1982; submitted Dec. 6, 1982; synoptic received Nov. 29, 1983.

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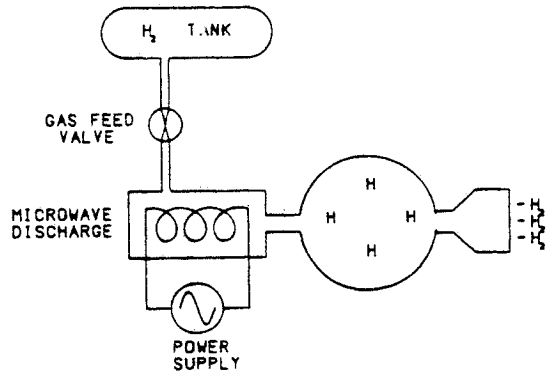

Fig. 1 Schematic drawing of the atomic hydrogen thruster.

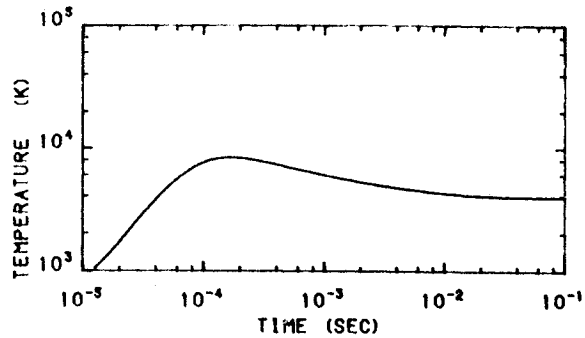

Fig. 2 Reaction chamber temperature vs time. The mass rate of atomic hydrogen in $\xi_H = 6.8 \times 10^{-5}$ kg/s into a Ti chamber of radius $R_s = 0.2$ m. The radius of the exit port is $R_p = 0.02$ m and $\beta_H = 0.15$.

Several important approximations have been made in this mathematical model. They are:

1) The surface recombination efficiency is assumed to be constant, thus the only temperature dependence of the surface recombination rate is the rate at which H atoms strike the walls.

2) Collisional dissociation with the walls is neglected.

3) The fraction of recombination energy transferred to the surface per surface recombination is constant during the thruster operation.

4) Nonreactive inelastic scattering from the chamber walls is neglected.

Using the model described above, the temperature, thrust, and other engine variables are calculated for a flow of atomic hydrogen into the chamber of $\xi_H = 6.8 \times 10^{-5}$ kg/s = 4.072×10^{22} atoms/s, with no buffer gas. The radius of the reaction chamber is $R_s = 0.2$ m with Ti walls and an exit port of radius $R_p = 0.02$ m. The fraction of energy lost to the walls per surface recombination is $\beta_H = 0.15$.

The number density of H, H_2, and M inside the reaction chamber is determined by integrating Eq. (2), and the density equations for H_2 and M, from $t = 0$ in steps of $\Delta t = 1.0 \times 10^{-7}$ s. The temperature is calculated using the equipartition theorem using the number densities of H, H_2, and M. The thrust is then determined using Eq. (3). The process is repeated until asymptotic values are reached at about $t = 0.1$ s.

Figure 2 shows the chamber temperature as a function of time. At approximately $t = 2.4 \times 10^{-4}$ s, the temperature begins to decrease and the density of H inside the chamber sharply increases, because thermal dissociation of H_2 molecules has become competitive with H atom recombination due to the high gas temperature.[8] Figure 3 shows the thrust vs time. The thrust increases monotonically with the time and reaches an asymptotic value of $F = 0.3$ N with a specific impulse of $I_{sp} = 500$ s. The gas temperature is $T = 4000$ K and the chamber pressure is 2.5 Torr.

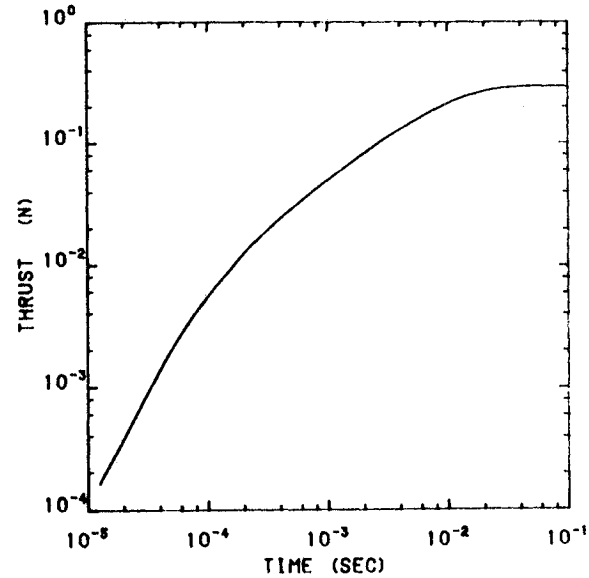

Fig. 3 The thrust developed vs time. Thruster parameters are as in Fig. 2.

Energy loss to the vibrational and rotational degrees of freedom of the H_2 molecules inside and exhausted from the reaction chamber is approximately 4 and 8% of the total input energy, respectively. Loss by exhaust of unreacted H atoms is approximately 8% of the total number of H atoms injected into the chamber.

Energy loss to the walls from surface recombination is about 55% and it is important to note that the low specific impulse is due primarily to this mechanism. However, our predicted loss is unrealistically large because the temperature dependence of the surface recombination rate and the rate at which energy is transferred to the surface from surface recombination has been neglected.

In summary, refinements of the mathematical model and optimization of thruster geometry and surface character will increase the performance of the propulsion system and it seems apparent that thrusts of $F = 0.6$ N with specific impulses of $I_{sp} = 1000$ s are achievable.

References

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