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Radiation-Enhanced Dissociation of Hydrogen in Nuclear Rockets

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The effect of radiation-induced dissociation of hydrogen gas in nuclear rockets is studied. The degree of dissociation is obtained by solving rate equations, which include the fast ion-induced dissociation and ionization of atomic and molecular hydrogens. Analytical formulas are used to estimate a change in the viscosity and the specific impulse. We have found that the fast ion-induced dissociation can theoretically play a role in enhancing the specific impulse for nuclear rocket concepts using hydrogen gas at low pressures (<0.1 MPa) and low temperatures (<3000 K). It is also shown that the specific impulse is enhanced by mixing helium-3, lithium-6, and boron-10 with hydrogen.

Nomenclature

c_p = heat capacity of hydrogen gas, J/kg/K
D = dissociation energy, J/mol
E_f = fission energy per reaction, MeV
G = number of molecules formed or lost per 100 eV of absorbed dose
I_{sp} = specific impulse, s
k_i = rate coefficient of reaction i, W^{-1}, $cm^{-3}\ s^{-1}$, or $cm^{-6}\ s^{-1}$
n_f = fissile fuel density, cm^{-3}
p = fuel gas pressure, MPa
$\dot{Q}_r$ = radiation energy deposition rate, W/cm^3 or W/cc
$\dot{q}_d(x)$ = energy deposition rate at distance x from solid nuclear material, W/cm^3
R_i = stopping range of fast ions in medium i, cm
T = effective temperature of gaseous fuel, K
w = radiation energy expended per ion-electron pair formation, eV
$[X]$ = particle density of species X, cm^{-3}
α = degree of hydrogen dissociation
γ_i = probability of energy loss to species i
ξ = mole fraction of fast ion producing species
σ_f = fission cross section, cm^2
ϕ_{th} = thermal neutron flux, $cm^{-2}\ s^{-1}$

Introduction

THE specific impulse of nuclear thermal rocket propulsions can be increased by using a light atomic gas (hydrogen) and raising the gas temperature at the reactor chamber.[1] Further enhancement is possible by recovering the dissociation energy of hydrogen molecules through recombination at the nozzle exit.[2]

Some thermal neutron-induced nuclear reactions taking place in nuclear reactors produce high-energy charged particles. These fast ions can ionize and dissociate molecules during the slowing down. Thus, hydrogen molecules can be effectively dissociated by adequately designing the reactor core so that fast ions could deposit most of their energy in hydrogen gas. Particularly, in reactor concepts using noncladded solid/liquid fuels of comparatively small size, fast ions (or fission fragments) easily escape the reacting medium, dissociating the hydrogen molecules. Some of these concepts are the fission fragment,[3] uranium arc,[4] liquid droplet,[5] and liquid annular[6] concepts.

In this article, we first make a chemical reaction model including fast ion-induced nonequilibrium ionization and dissociation, and compute the degree of dissociation. The effect of enhanced dissociation on the specific impulse is evaluated by using a simple analytical formula. We also examine the impact of fast ion-induced dissociation on the thermophysical properties of the hydrogen, i.e., viscosity. An assessment is made whether the effect is important for the proposed nuclear rocket propulsion concepts. To take further advantage of the fast-ion induced dissociation, a technique of mixing fast ion-producing atoms in hydrogen gas is proposed.

Radiation-Induced Dissociation

Physical Model

Radiation (gammas and charged particles) induces dissociation of hydrogen molecules by imparting its kinetic energy to molecules. Hence, the degree of dissociation of hydrogen gas exposed with radiation is different from that of gas in thermal equilibrium. In this section, we develop a physical model needed to compute α, which is defined as the number of hydrogen atoms divided by the total number of particles (atoms and molecules). It is easy to show that the population of negative hydrogen ions is small compared with the electron population. Thus, we assume that only five particle species (H, H_2, H^+, H_2^+, and electrons) are present in the hydrogen gas at the gas conditions of interest (i.e., p = 0.01 to 10 MPa, and T = 2000 to 4000 K). For these species, eight chemical reactions given in Table 1 are considered.[7-12] Note that radiation induces both ionization and dissociation of hydrogen molecules, and dissociative ionization is less likely to occur.[7]

Steady-state rate equations are given for H_2 H, H_2^+, H^+ in a spatially uniform gas:

$$k_4[H]^2[M] - (k_1 + k_2)\gamma_2\dot{Q}_r - k_5[H_2][M] - k_6[H_2][e] = 0 \quad (1)$$

$$2k_2\gamma_2\dot{Q}_r + 2k_5[H_2][M] + 2k_6[H_2][e] + k_7[H^+][e]^2 + 2k_8[H_2^+][e] - k_3\gamma_1\dot{Q}_r - 2k_4[H]^2[M] = 0 \quad (2)$$

$$k_1\gamma_2\dot{Q}_r - k_8[H_2^+][e] = 0 \quad (3)$$

$$k_3\gamma_1\dot{Q}_r - k_7[H^+][e]^2 = 0 \quad (4)$$

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Applying G values,[13] one can represent the rate coefficients k_i (i = 1, 2, 3) for radiation-induced ionization and dissociation terms as

$$k_i = (G/100) \times [1/(1.6 \times 10^{-19})\ [\mathrm{W}^{-1}] \quad (5)$$

Since the ionization degree of the gas is low, i.e., below 10^{-3}, one can assume that whole energy is absorbed by neutral hydrogen atoms or molecules. An approximate formula for the probability of the energy absorption by species i in a gaseous mixture of species i and j is given by[14]

$$\gamma_i = \frac{[X_i]}{[X_i] + a_{ij}[X_j]} \quad (6)$$

where a_{ij} is the ratio of the effective atomic mass of species i and j. For a mixture of hydrogen atoms and molecules, the ratio is approximately two. Then, using the dissociation degree α, the probabilities γ_1 and γ_2 for hydrogen atoms and molecules are represented by

$$\gamma_1 = \frac{\alpha}{2 - \alpha} \quad (7)$$

$$\gamma_2 = \frac{2(1 - \alpha)}{2 - \alpha} \quad (8)$$

Charge neutrality of the gas requires

$$[e] - [\mathrm{H}^+] - [\mathrm{H}_2^+] = 0 \quad (9)$$

For a weakly ionized gas, the total number of particles, N, in the gas is fixed for given gas pressure and temperature:

$$[\mathrm{H}] + [\mathrm{H}_2] = N \quad (10)$$

There are six equations for five unknowns. Therefore, Eqs. (1), (3), (4), (9), and (10) are sufficient to determine the solution uniquely. The solution is provided seminumerically. First, Eqs. (3), (4), and (9) are solved for $[\mathrm{H}^+]$, $[\mathrm{H}_2^+]$, and $[e]$ by assuming $[\mathrm{H}]$ and $[\mathrm{H}_2]$ in γ_1 and γ_2. Then, using this solution, Eq. (1) with Eq. (10) are solved for $[\mathrm{H}]$ and $[\mathrm{H}_2]$. Iterations are made until the value for $[\mathrm{H}_2]$ converges with a given precision.

Characteristics of Nonequilibrium Dissociation

Rate coefficients used with Eqs. (1–4) for the following analysis are shown in Table 1. There is a simple relationship between the G value and the w value[13]: $G = 100/w$. Hence, the G values for ionization (i.e., reactions 1 and 3) are estimated by using empirical formulas for fast electrons relating the w value with the ionization potential.[8] These values are correct for other types of charged particles within 10%. The G value for the dissociative reaction (reaction 2) is computed from the w value for the excitation reaction between fast electrons and molecules. Here, we assume that the excitation always leads to dissociation.[7] Since excited molecules either decay by emitting a photon or dissociate into two atoms, the assumption may yield a larger value for the G value than the true value.

Figure 1 shows the computed degree of hydrogen dissociation as a function of gas temperature for various gas pressures, 0.01, 0.1, and 1 MPa. Solid curves represent the equilibrium solutions. Nonequilibrium solutions (dotted curves) are obtained for various energy deposition rates. The figure indicates that a significant enhancement of dissociation is achieved for gases at temperatures below 3000 K and pressures less than 0.1 MPa. For example, the degree of dissociation of a gas at 0.01 MPa and 3000 K is 0.41 in equilibrium; whereas it is 0.55 when the ra-

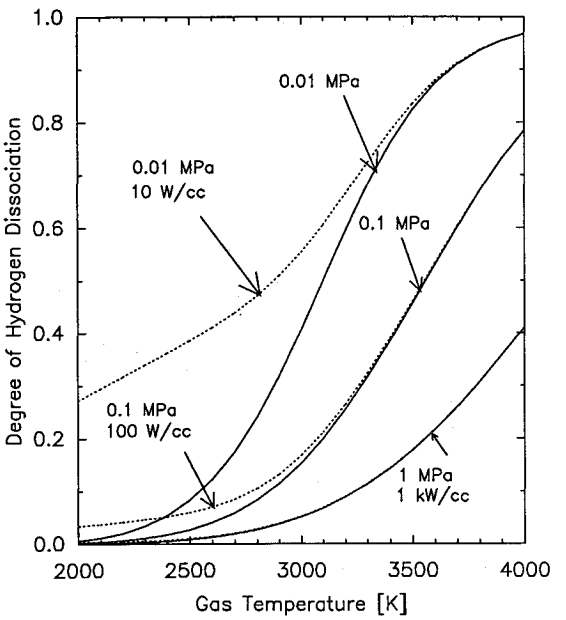

Fig. 1 Degree of dissociation of hydrogen gas vs gas temperature.

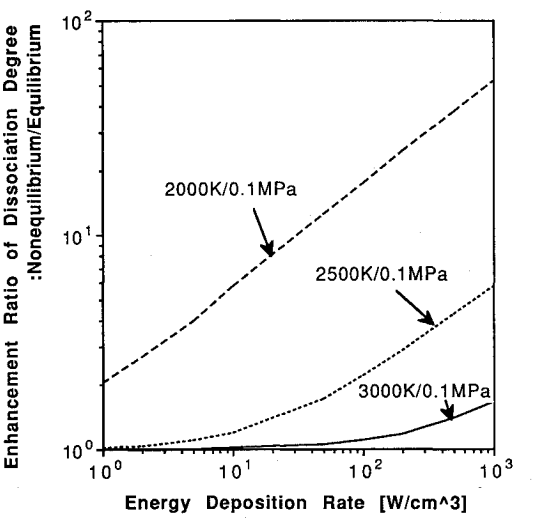

Fig. 2 Degree of dissociation vs energy deposition rate.

Table 1 Atomic reaction and rate coefficients

ID	Reaction	Reaction rate coefficient, k_i	Reference
1	$H_2 + X \rightarrow H_2^+ + e + X$[a]	$1.72 \times 10^{17}\ \mathrm{W}^{-1}$	8
2	$H_2 + X \rightarrow H + H + X$	$1.89 \times 10^{17}\ \mathrm{W}^{-1}$	8
3	$H + X \rightarrow H^+ + e + X$	$2.71 \times 10^{17}\ \mathrm{W}^{-1}$	9
4	$H + H + M \rightarrow H_2 + M$[b]	$6.34 \times 10^{-34}(T/2870)^{-1.2}\ \mathrm{cm}^6\ \mathrm{s}^{-1}$	10
5	$H_2 + M \rightarrow H + H + M$	$3.15 \times 10^{-10} \exp(-95{,}500/RT)\ \mathrm{cm}^3\ \mathrm{s}^{-1}$	10
6	$H_2 + e \rightarrow H + H + e$	$3.17 \times 10^{-13} \exp(-203/RT)\ \mathrm{cm}^3\ \mathrm{s}^{-1}$	11
7	$H^+ + e + e \rightarrow H + e$	$8.7 \times 10^{-20}(T/298)^{-4.5}\ \mathrm{cm}^6\ \mathrm{s}^{-1}$	9
8	$H_2^+ + e \rightarrow H + H$	$1.6 \times 10^{-8}(T/300)^{-0.43}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$	12

[a]X represents fast ions and fast electrons. [b]M represents neutral particles, i.e., H or H_2.

diation energy deposition rate is 10 W/cm³. The enhancement is larger at lower temperatures. As the gas pressure increases, the radiation effect becomes smaller. The effect is negligible for gases at 1 MPa even if very high radiation energy (1 kW/cm³) is deposited.

The dependence of dissociation on the energy deposition rate is shown in Fig. 2, in which the gas temperatures of 2000, 2500, and 3000 K are used with a gas pressure of 0.1 MPa. In the figure, the ordinate is the ratio of dissociation degree for nonequilibrium case to the equilibrium value. Note that the enhancement in the dissociation is nearly proportional to the energy deposition rate for a low temperature gas (T = 2000 K); it increases from 2 to 50 as the energy deposition rate increases from 1 to 1000 W/cm³.

Reaction rate data suffer from large uncertainty; in particular, the G values for heavy charged particles such as fission fragment ions are not well-known. Hence, it is important to examine the sensitivity of the results (the dissociation degree)

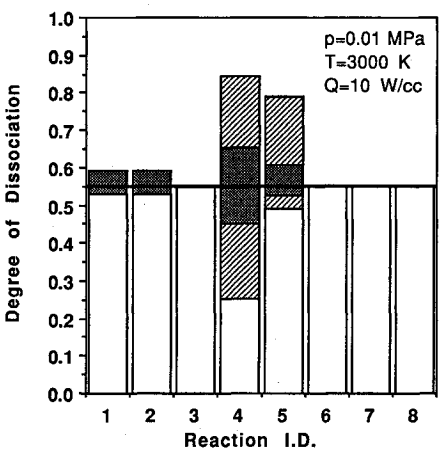

Fig. 3 Sensitivity of dissociation degree to variation in rate coefficients. Shaded areas indicate possible variations of dissociation degree for the reaction rate coefficients varied from $\frac{1}{2}$ to 2 times of the reference values. Hatched areas are for the rate coefficients varied from $\frac{1}{10}$ to 10 times the reference values.

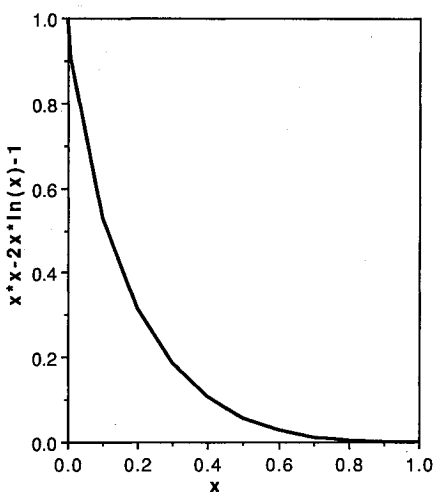

Fig. 4 Energy deposition rate profile of charged particles emitted from solid surface.

to the data uncertainty. Figure 3 presents the variation of the dissociation degree when the eight reaction-rate coefficients are independently varied. For these calculations, the G values are varied by a factor of two and other coefficients are varied up to an order of magnitude. One sees the significance of the data accuracy with the G values for the ionization and dissociation reactions of molecular hydrogens (reactions 1 and 2) and the recombination and dissociation reactions of neutral hydrogens (reactions 4 and 5). The uncertainty in the rate coefficients of the other four reactions has little impact on the dissociation degree; this suggests that these reactions are not important for predicting the dissociation degree. There are a number of measurements of the reaction rates of reactions 4 and 5. Since the degree of dissociation is very sensitive to these coefficients, however, more reliable data are needed. Experimental measurements of the G values for the ionization and dissociative reactions of hydrogen molecules have not been done, to the author's knowledge, for fast-ions of our interests (i.e., H, ³H, ⁴He, ⁷Li, and fission fragments). Since the G values are key data to evaluate the feasibility of radiation-induced dissociation, systematic experimental measurements must be undertaken.

Radiation Energy Deposition in Gas

Neutrons and high-energy photons (gammas) are present in a nuclear reactor. Neutrons themselves do not deposit the energy to hydrogen gas very effectively. There are atoms producing fast ions upon interacting with thermal neutrons such as helium-3, lithium-6, boron-10, and uranium-235, and charged particles expend the energy very effectively in hydrogen gas. Such atoms can be either mixed with the gas or be coated on the solid surface facing the hydrogen gas in order to take advantage of fast ion-induced dissociation.

First, we consider a hydrogen gas mixed with fast-ion producing species. When the atoms are mixed uniformly and the size of the cavity is sufficiently large compared with the mean range of the fast ions, the fast ions expend the energy uniformly in the gas. Then, the energy deposition rate per unit volume is given by

$$\dot{Q}_r = E_f n_f \sigma_f \phi_{\text{th}} \tag{11}$$

Note that the energy deposition rate is proportional to the particle density of the fast ion-producing species or the partial pressure of the species if the gas obeys the perfect gas law. Table 2 shows the energy deposition rate along with E_f and σ_f for $n_f = 2.41 \times 10^{18}$ cm^{-3} (or a gas at 0.1 MPa and 3000 K) and $\phi_{\text{th}} = 10^{16}$ cm^{-2}s^{-1}. Here, we consider a nuclear reactor yielding a relatively high neutron flux.

When fast ion-producing species are coated on a solid surface, the fast ions produced in the solid material lose their energy in the solid medium before they escape the medium; the rest of the energy is deposited in the hydrogen gas. The energy deposition rate as a function of the distance from the solid wall, z, can be computed by using the following analytical formula derived by Nguyen and Grossman for the slab geometry[15]:

$$\dot{q}_d(x) = (\dot{Q}_r/2)(R_1/R_2)[1 + 2x\,\ell n(x) - x^2] \tag{12}$$

where $x = z/R_2$. R_1 and R_2 are the stopping range of fast ions in the solid medium and hydrogen gas, respectively. Note that Eq. (12) is derived by neglecting the nuclear scattering and

Table 2 Energy production of candidate nuclear reactions

Reaction	Q value, MeV	Thermal neutron cross section, b	$\dot{Q}_r$, W/cm³ [a]
$^3He + n \rightarrow H + {}^3H$	+0.763	5300	15.6
$^6Li + n \rightarrow {}^4He + {}^3H$	+4.78	1000	18.5
$^{10}B + n \rightarrow {}^4He + {}^7Li$	+2.79	3800	41.0
$^{235}U + n \rightarrow$ heavy ions	+168	590	383

[a] $\phi_{\text{th}} = 10^{16}$ cm^{-2} s^{-1}, p = 0.1 MPa and T = 3000 K.

Table 3 Energy deposition of charged particles in gas facing solid wall

Material[a]	$\dot{Q}_r$, kW/cm^3 [b]	R_1, μm[c]	R_2, cm[d]	$\dot{q}_d(0)$, W/cm^3
Li	26.6	15.9	39.8	0.532
B	440	2.42	23.4	2.28
U	550	5.67	34	4.78
$LiAlO_2$	13.4	7.59	39.8	0.128
B_4C	371	4.24	23.4	3.14
UO_2	313	9.26	34	4.25

[a]Natural isotope composition is used except for U and UO_2, which are 7.2% enriched by ^{235}U.
[b]$\phi_{th} = 10^{16}$ cm^{-2} s^{-1}.
[c]Only ranges for ions with a longer range are shown.
[d]For hydrogen gas, $p = 0.1$ MPa and $T = 2000$ K, or $[H_2] = 3.62 \times 10^{18}$ cm^{-3}.

Table 4 Nuclear thermal propulsion concepts

Concept	p, MPa	T, K	ϕ_{th}, cm^{-2} s^{-1}	I_{sp}, s	Ref.
Solid core	5–10	3000	10^{14}	900–1100	20
Low pressure	0.1–1.0	3500	10^{14}	900–1300	2
Fission fragment	6.8	3000	10^{14}	1000	3
Uranium arc	0.2	2400	10^{14}	1800	4
Liquid droplet	10	6000	10^{16}	2000	5
Liquid annular	1.0	6000	10^{15}	2000	6
Open-cycle gas core	100	10^5	10^{16}	5000	21

applying the Thomas-Fermi approximation for the effective charge number of fast ions. The function inside the parentheses in the right-side of the equation indicates that the energy deposition rate quickly drops in the vicinity of the wall, and it vanishes at the distance equal to the stopping range as shown in Fig. 4.

The stopping range of fast ions are inversely proportional to the mass density of the transporting medium. It also depends on the atomic and mass numbers of the fast ions and the medium, and the initial energy of the fast ions.[16,17]

Using Eqs. (11) and (12), the energy deposition rate at the solid surface are computed for natural Li, B, B_4C, $LiAlO_2$, U, and UO_2 (7.2% enriched by ^{235}U). The results are shown in Table 3. For $p = 0.1$ MPa and $T = 2000$ K, the energy deposition rate varies from 0.1 to 5 W/cm^3. Note that the energy deposition rate is proportional to the hydrogen gas pressure and the thermal neutron flux.

Applications to Nuclear Rockets

Impact of Hydrogen Dissociation on Viscosity

Thermophysical and transport properties of gases significantly affects the heat transfer and fluid mechanics in nuclear reactors. The viscosity of molecular hydrogen gas is larger than that of atomic hydrogen gas. For example, the viscosity for the former is 402.8 micropoises at 3000 K, while it is 332.7 μP for the latter.[18] Thus, the radiation-induced dissociation of hydrogen molecules leads to a gas with smaller viscosity than a gas in thermal equilibrium. A theoretical estimation of viscosity as a function of the degree of dissociation is made by using a mixture rule.[19] The result shows that the viscosity decreases 3.5% as the dissociation degree increases from 0 to 30%. The thermal conductivity also depends on the dissociation degree. But, the impact of the nonequilibrium dissociation is even smaller than that for the viscosity. Therefore, the effect of the fast ion-induced dissociation on the transport properties of hydrogen gas is not significant in nuclear rockets.

Impact of Hydrogen Dissociation on Specific Impulse

The fast ion-induced dissociation yields a higher specific impulse if the dissociation energy can be converted to the kinetic energy of the hydrogen molecules at the nozzle exit. To estimate the impact of the nonequilibrium dissociation on the specific impulse, we use a simplified formula for the specific impulse.[1] We consider a hydrogen gas mixed with an atomic species X with atomic mass A_X. Here, the mole fraction of species X is denoted by ξ. Assuming that the dissociation energy is fully recoverable for the kinetic acceleration, a formula for the ratio of the specific impulse for nonequilibrium gases I^*_{sp} to that for equilibrium gases I^0_{sp} can be derived. The result is

$$\frac{I^*_{sp}}{I^0_{sp}} = \sqrt{\frac{M(\alpha_0)}{M(\alpha^*)} \frac{\eta(\alpha^*) + (D/4c_pT)(1-\xi)\alpha^*}{\eta(\alpha_0) + (D/4c_pT)(1-\xi)\alpha_0}} \tag{13}$$

where α^* and α_0 are the dissociation degrees for the nonequilibrium and equilibrium gases, respectively. Here, the function $\eta(\alpha)$ is given by

$$\eta(\alpha) = [1 - (2\alpha/7)](1-\xi) + (5/7)\xi \tag{14}$$

The average atomic mass of a particle $M(\alpha)$ is defined by

$$M(\alpha) = (1-\xi)(2-\alpha) + \xi A_X \tag{15}$$

The dissociation energy is $D = 4.32 \times 10^5$ J/mol for hydrogen molecules.[10] The specific heat for hydrogen molecules $c_p = 1.46 \times 10^4$ J/kg/K is used by assuming that it is independent of the gas pressure. Figure 5 shows the ratio as a function of temperature for a pure hydrogen gas (i.e., $\xi = 0$) with $p = 0.01$ MPa/$\dot{Q}_r = 1$, 10 W/cm^3 and $p = 0.1$ MPa/$\dot{Q}_r = 100$ W/cm^3. At low temperatures, the impact of nonequilibrium dissociation is significant; e.g., the effect yields a 12 and 28% increase in the specific impulse at $p = 0.01$ MPa and $T = 2000$ K for $\dot{Q}_r = 1$ and 10 W/cm^3, respectively.

Examination of Propulsion Concepts

Some nuclear thermal propulsion concepts can take advantage of the nonequilibrium dissociation effect. Table 4 lists the typical gas pressure and temperature in the reactor chamber for seven concepts. As previously stated, the radiation-induced dissociation is significant for systems with a low pressure, a low temperature, and a high radiation energy deposition.

Radiation-induced dissociation plays no role in the specific impulse enhancement with the solid core and low pressure thermal nuclear rockets because fission fragments cannot escape from solid nuclear fuels enclosed in a cladding material.[12,20] The fission fragment rocket concept takes advantage of fission fragments emitted from uranium coated solid wall to heat the propellant.[3] It uses a rather high gas pressure, however. Thus, it is unlikely for the nonequilibrium effect to be important. The uranium arc concept uses fission fragments emitted from fissioning plasma contained in arcs to achieve

additional ionization and dissociation of hydrogen gas.[4] Since its gas pressure and temperature are relatively low, the nonequilibrium process plays a significant role. The uranium atoms or droplets are uniformly dispersed for the liquid droplet concept.[5] Thus, the energy deposition rate given by Eq. (11) can be realized. A problem, however, is its high gas pressure and temperature. For these design values, the nonequilibrium dissociation does not yield significant additional dissociation over that by the equilibrium dissociation. For the liquid annular concept,[6] the effect is even smaller than the liquid droplet concept because the radiation energy deposition is limited by the fission fragment flux coming out from the annular liquid fuel. For the conventional open-cycle gas core concept,[21] a similar argument can be made. Since the fission fragment source is not in the hydrogen gas, the fission fragments only affect the property of the gas in the vicinity of the central fuel core.

It is very unlikely for most of the proposed concepts to obtain sufficiently high radiation energy deposition in the gas. Mixing fast ion-producing species with hydrogen is an attractive idea to take advantage of the nonequilibrium dissociation. A drawback, however, is that this increases the average mass of the propellant. By applying Eq. (13), the ratios of the specific impulse for gas mixtures of hydrogen and fast ion-producing species to that of the same gases without the additional dissociation due to fast ions are computed. The results are shown in Fig. 6 for ^{3}He, ^{6}Li, and ^{10}B. Here, the total pressure of the gas is 0.02 MPa. The partial pressure of hydrogen gas is 0.01 MPa (i.e., $\xi = 0.5$). For these calculations, the energy deposition rates obtained before (see Table 2) are used. One sees that despite the heavy mass, the specific impulse considerably increases for the gas mixed with atoms, producing a large nuclear energy deposition. Mixing hydrogen gas with ^{3}He and ^{10}B yields a 10 and 16% increase in the specific impulse at 2000 K, respectively. Note that in this temperature range, uranium and boron are in liquid state. Also, the estimate is made by ignoring interactions among hydrogens and the fast ion-producing species. Thus, the result indicates only a feasibility of the proposed technique.

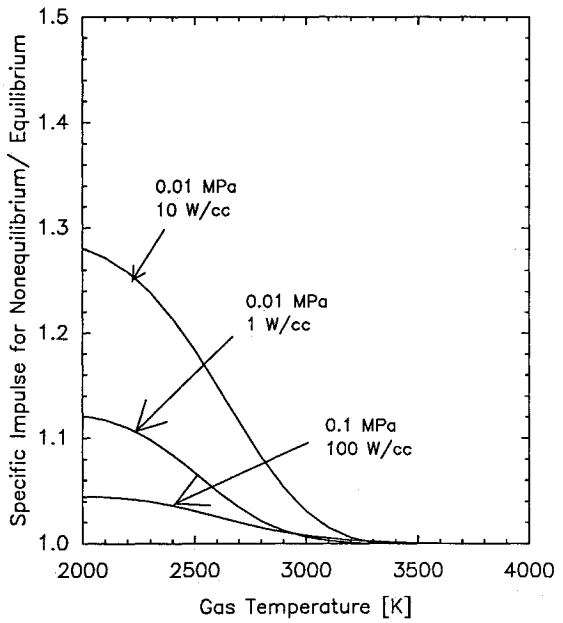

Fig. 5 Impact of nonequilibrium dissociation on specific impulse.

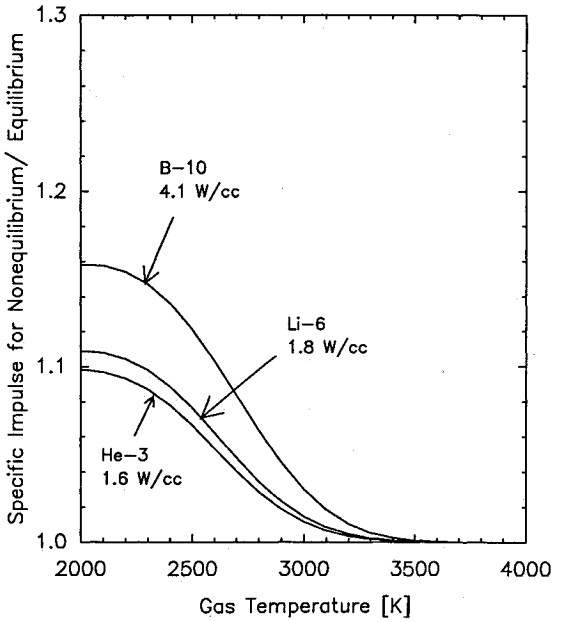

Fig. 6 Specific impulse enhancement in gas mixtures.

Conclusions

We have evaluated the effect of radiation-induced dissociation on the viscosity of hydrogen gases and the specific impulse of nuclear rockets. The degree of dissociation is computed by formulating a chemical reaction model. Energy deposition rates of fast ions produced by nuclear reacting atoms dispersed uniformly in a hydrogen gas and present in solid/liquid fuels are estimated by applying simple analytical formulas.

We have found that the fast ion-induced dissociation increases the dissociation degree of gases at low pressures (<0.1 MPa) and low temperatures (<3000 K), resulting in an enhancement of the specific impulse. For example, 1 W/cm^3 of radiation energy deposition in hydrogen gas at 0.01 MPa and 2000 K leads to 12% increase in the specific impulse. Note that the results could be affected by the data of reaction rate coefficients, notably, the G values for radiation-induced ionization and dissociation reactions of hydrogen molecules. To reduce the uncertainty stemming from the data uncertainty, we suggest experimental measurements of the G values for ionization and dissociation of hydrogen molecules by fast ions and the rate coefficients of three-body recombination and two-body dissociation reactions of hydrogen.

Some proposed nuclear rocket concepts are studied to examine whether the fast ion-induced dissociation has any effect. It is found that for most concepts, the effect is not significant because of either a high pressure or a high temperature of the hydrogen gas. Then, a technique of mixing fast ion-producing species with hydrogen gas is proposed to take advantage of the effect. We have shown that a mixture of 50% hydrogen and 50% helium-3 enhances the specific impulse by more than 10% at 0.02 MPa and 2000 K. The present results can be used to design a nuclear rocket having a relatively low fuel and propellant temperature without degrading the high specific impulse capability, thus, enabling us to design a more reliable nuclear rocket engine.

Acknowledgment

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References

[1]Sutton, G. P., and Ross, D. M., *Rocket Propulsion Elements, An Introduction to the Engineering of Rockets*, 4th ed., Wiley, New York, 1976, p. 53.

[2]Knoll, D. A., "Computational Study of Nonequilibrium Hydrogen Flow in a Low Pressure Nuclear Thermal Rocket Nozzle," *Proceedings of Ninth Symposium on Space Nuclear Power Systems*, edited by M. S. El-Genk and M. D. Hoover, American Inst. of Physics, CONF-920104, New York, 1992, pp. 943–949.

[3]Suo-Anttila, A. J., Parma, E. J., Wright, S. A., Vernon, M. E., and Pickard, P. S., "A Fission Fragment Reactor Concept for Nuclear Space Propulsion," *Fusion Technology*, Vol. 20, No. 4, Pt. 2, 1991, pp. 725–729.

[4]Watanabe, Y., Maya, I., Vitali, J., and Schneider, R. T., "Uranium Arc Fission Reactor for Space Propulsion," *Proceedings of Eighth Symposium on Space Nuclear Power Systems*, edited by M. S. El-Genk and M. D. Hoover, American Inst. of Physics, CONF-910116, New York, 1991, pp. 625–630.

[5]Anghaie, S., "Uranium Droplet Core Nuclear Rocket," AIAA Paper 91-3514, Sept. 1991.

[6]Maise, G., Lazareth, O. W., Horn, F., Powell, J. R., Ludewig, H., and Lenard, R. X., "The Liquid Annular Reactor System (LARS) Propulsion," *Proceedings of Eighth Symposium on Space Nuclear Power Systems*, edited by M. S. El-Genk and M. D. Hoover, American Inst. of Physics, CONF-910116, New York, 1991, pp. 618–624.

[7]Massey, H. S. W., and Gilbody, H. B., *Electronic and Ionic Impact Phenomena, Volume IV: Recombination and Fast Collisions of Heavy Particles*, 2nd ed., Clarendon Press, London, 1974, p. 2963.

[8]Platzman, R. L., "Total Ionization in Gases by High-Energy Particles: An Appraisal of Our Understanding," *International Journal of Applied Radiation and Isotopes*, Vol. 10, No. 283, 1961, pp. 116–127.

[9]Watanabe, Y., Appelbaum, J., and Maya, I, "Two-Temperature Model of Helium Plasmas with Fast-Ion Induced Non-Equilibrium Ionization," AIAA Paper 90-1613, June 1990.

[10]Troe, J., and Wagner, H. G., "Unimolecular Dissociation of Small Molecules," *Physical Chemistry of Fast Reactions, Volume 1. Gas Phase Reactions of Small Molecules*, edited by B. P. Levitt, Plenum Press, London, 1973, pp. 1–80.

[11]McCay, T. D., and Dexter, C. E., "Chemical Kinetics Performance Losses for a Hydrogen Laser Thermal Thruster," *Journal of Spacecraft and Rockets*, Vol. 24, No. 4, 1987, pp. 372–376.

[12]Mitchell, J. B. A., "The Dissociative Recombination of Molecular Ions," *Physics Report*, Vol. 186, No. 5, 1990, pp. 215–248.

[13]Klassen, N. V., "Primary Products in Radiation Chemistry," *Radiation Chemistry, Principles and Applications*, edited by Farhataziz and M. A. J. Rodgers, VCH Publishers, New York, 1987, pp. 29–64.

[14]Christophourou, L. G., *Atomic and Molecular Radiation Physics*, Wiley—Interscience, London, 1971, p. 47.

[15]Nguyen, D. H., and Grossman, L. M., "Ionization by Fission Fragments Escaping from a Source Medium," *Nuclear Science and Engineering*, Vol. 30, No. 2, 1967, pp. 233–241.

[16]Kahn, S., Harman, R., and Forgue, V., "Energy Distributions of Fission Fragments from Uranium Dioxide Films," *Nuclear Science and Engineering*, Vol. 23, No. 1, 1965, pp. 8–20.

[17]Northcliffe, L. C., and Schilling, R. F., "Range and Stopping Power Tables for Heavy Ions," *Nuclear Data Tables, Part A*, Vol. 7, Nos. 3 and 4, 1970, pp. 233–463.

[18]Svehla, R. A, "Estimated Viscosities and Thermal Conductivities of Gases at High Temperature," NASA TR R-132, 1962.

[19]Bird, R. B, Stewart, W. E., and Lightfoot, E. N., *Transport Phenomena*, Wiley, New York, 1960, p. 24.

[20]Angelo, J. A., Jr., and Buden, D., *Space Nuclear Power*, Orbit Book, Malabar, FL, 1985, pp. 110–196.

[21]Kascak, A., "Nozzle and Cavity Wall Cooling Limitations on Specific Impulse of a Gas-Core Nuclear Rocket," *Proceedings of Second Symposium on Uranium Plasmas: Research and Applications*, AIAA, New York, Nov. 1971, pp. 173–178.