PERFORMANCE ASSESSMENT OF LOW PRESSURE NUCLEAR THERMAL PROPULSION

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INTRODUCTION

An increase in Isp for nuclear thermal propulsion systems is desirable for reducing the propellant requirements and cost of future applications, such as the Mars Transfer Vehicle. Several previous design studies have suggested that the Isp could be increased substantially with hydrogen dissociation/recombination. Hydrogen molecules (H_2), at high temperatures and low pressures, will dissociate to monatomic hydrogen (H), see Figure 1. The reverse process (i.e., formation of H_2 from H) is exothermic. The exothermic energy in a nozzle increases the kinetic energy and therefore increases the Isp.

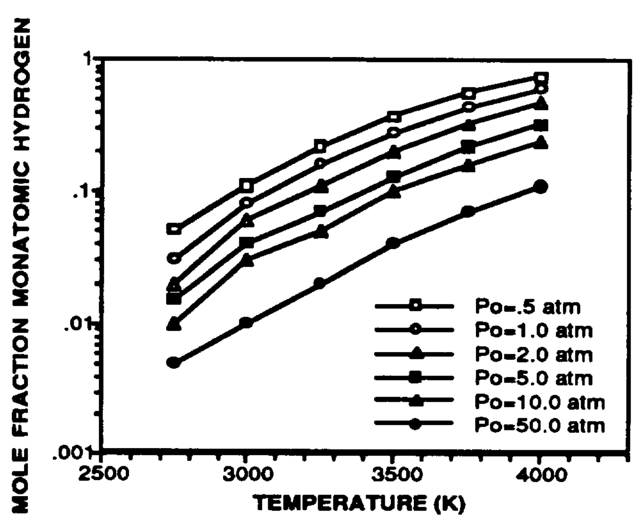

Figure 1. Mole fraction of hydrogen dissociated to monatomic hydrogen[1]

The low pressure nuclear thermal propulsion system (LPNTP) system is expected to maximize the hydrogen dissociation/recombination and Isp by operating at high chamber temperatures and low chamber pressures. The process involves hydrogen flow through a high temperature, low pressure fission reactor, and out a nozzle. The high temperature (~3000 K) of the hydrogen in the reactor is limited by the temperature limits of the reactor material. The minimum chamber pressure is about 1 atm because lower pressures decrease the engines thrust to weight ratio below acceptable limits. This study assumes that hydrogen leaves the reactor and enters the nozzle at the 3000 K equilibrium dissociation level.

Hydrogen dissociation in the reactor does not affect LPNTP performance like dissociation in traditional chemical propulsion systems, because energy from the reactor resupplies energy lost due to hydrogen dissociation. Recombination takes place in the nozzle due primarily to a drop in temperature as the Mach number increases. However, as the Mach number increases beyond the nozzle throat, the static pressure and density of the flow decreases and minimizes the recombination. The ideal LPNTP Isp at 3000 K and 10 psia is 1160 seconds due to the added energy from fast recombination rates. The actual Isp depends on the finite kinetic reaction rates which affect the amount of monatomic hydrogen recombination before the flow exits the nozzle.

A LPNTP system has other technical issues (e.g. flow instability and two-phase flow) besides hydrogen dissociation/recombination which affect the systems practicality. In this study, only the effects of hydrogen dissociation/recombination are examined.

KINETICS MODEL

The two-dimensional kinetics (TDK) nozzle performance computer program[2] was used to determine the effect of various parameters on hydrogen dissociation/recombination and Isp in a conical nozzle. TDK simulates an invisid flow from the start of nozzle contraction to the nozzle exit. Boundary layer calculations and heat loss were neglected. The one-dimensional equilibrium (ODE) option of TDK was used to calculate the upper Isp limit due to shifting molar species concentrations in the expansion process. The one-dimensional frozen (ODF) option of TDK was used to calculate the lower Isp limit due to frozen molar species concentrations in the expansion process. The one-dimensional kinetics (ODK) option of TDK accounts for the effects of finite chemical kinetics. Both ODE and ODK calculations provide data in the axial direction only, and the properties for each cross-section are constant. The TDK option calculates changes in the radial direction and uses two third-body reactions for hydrogen (H_2, H):

$$H + H + H \Leftrightarrow H_2 + H \quad (1)$$

$$H + H + H_2 \Leftrightarrow H_2 + H_2 \quad (2)$$

The reaction rate coefficient equations (k_{H2} and k_H) for each of the above reactions are in the Arrhenius form, which is written as:

$$k = AT^{-N}e^{\frac{-1000B}{RT}} \quad (3)$$

Table 1 shows the forward kinetic k_H and k_{H2} equations obtained from Cohen & Westberg (C&W)[3], from the national aerospace plane (NASP) rate constant committee of the NASP high-speed propulsion technology team[4], and from the default equations used in the TDK. The C&W equations were used in this study.

RESULTS

Pressure Sensitivity

The ODK and TDK Isp curves are close to equilibrium (ODE) at high stagnation chamber pressure (Po), but approach frozen flow (ODF) at low Po, Figure 2. As Po decreases from 1000 psia to 100 psia, both ODK Isp and TDK Isp increase. At 100 psia, Figure 2 shows the ODK Isp to be approximately 1007 seconds, and 27 seconds greater than the ODF Isp. From 100 psia down to 10 psia, the ODK Isp and TDK Isp change is minimal. Below 10 psia, the ODK Isp increases like frozen flow due to a lower average molecular weight caused by greater dissociation and less recombination. At 10 psia, the ODK Isp is 1005 seconds, but is only 14 seconds greater than the ODF Isp.

The mole fraction of monatomic hydrogen (X_H) entering the nozzle is 17.3% with Po at 10 psia and 5.9% with Po at 100 psia, see Figure 4. The X_H decreases in the nozzle due to monatomic hydrogen recombination. Inside the nozzle, there is 3% recombination at 100 psia and 1.25% recombination at 10 psia. Greater recombination from higher pressures and flow densities is the reason why the difference between ODK Isp and ODF Isp is greater at 100 psia.

Temperature Sensitivity

Plots illustrating Isp versus Po at 3200 K are shown in Figure 3. The Isp is almost constant from 10 psia to 100 psia. At 100 psia, the ODK Isp is 1066 seconds and 45 seconds greater than the ODF Isp. Thus, increasing the stagnation chamber temperature (To) from 3000 K to 3200 K will increase the ODK Isp by approximately 60 seconds.

Table 1. Kinetic reaction rate coefficient equations.

$H + H + M \rightleftharpoons H2 + M$

STANDARD TDK[2]		
M=Ar,	k= 6.4*10**(17)T**(-1)	
M=H,	k=25*k(Ar)	
M=H2,	k=4*k(Ar)	
COHEN AND WESTBERG[3]		
M=H:	k=1*10**(15)	LOW
	k=3.2*10**(15)	NOMINAL
	k=1.0*10**(16)	HIGH
M=H2:	k=5*10**(16)*T**(-.6)	LOW
	k=1.0*10**(17)*T**(-.6)	NOMINAL
	k=2.0*10**(17)*T**(-.6)	HIGH
NASP EQUATIONS[4]		
M=H:	k=1.5 * 10**(19)* T**(-1.0)	
M=H2:	k=1.8 * 10**(18)* T**(-1.0)	

UNITS=CM**6/(MOLE**2*SEC)

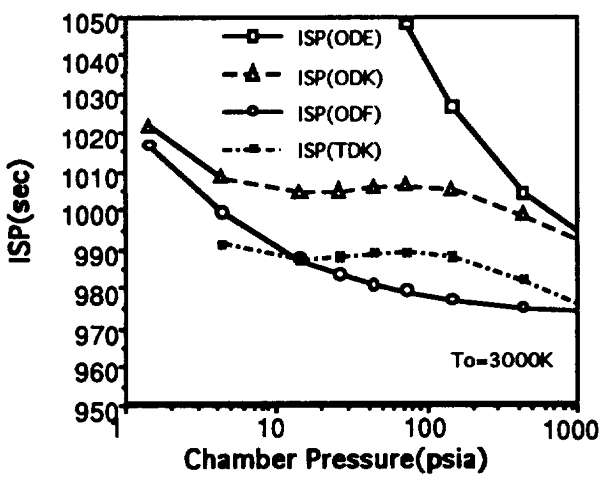

Figure 2. Isp vs. Po.

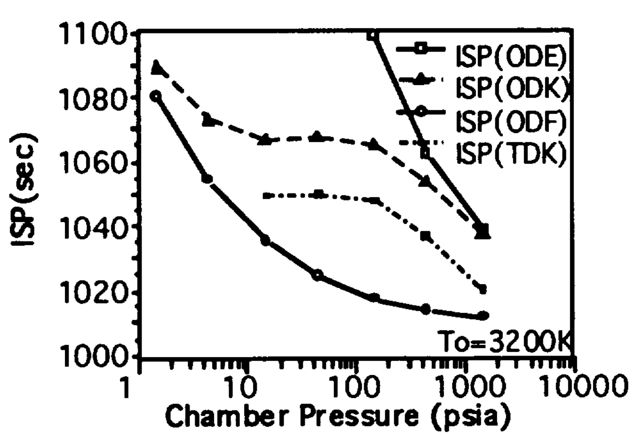

Figure 3. Isp vs. Po at 3200 K.

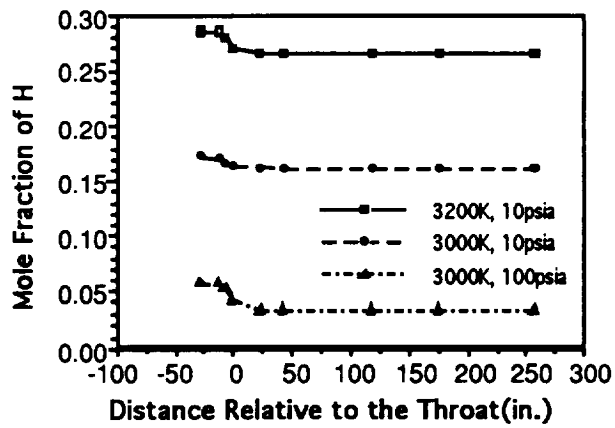

Figure 4. X_H vs. axial nozzle position.

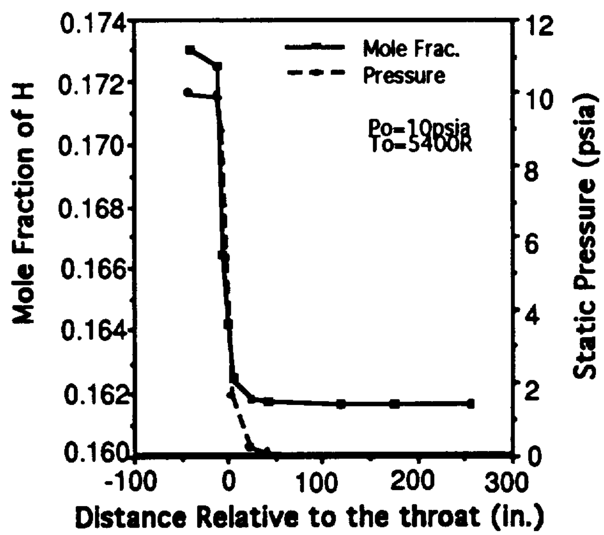

Figure 5. X_H and P vs. X (Po=10 psia).

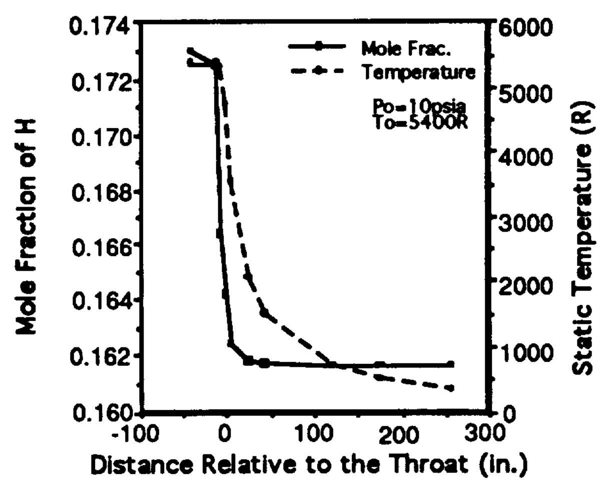

Figure 6. X_H and T vs. X (Po=10 psia).

Increasing To from 3000 K to 3200 K, at 10 psia, increases X_H at the nozzle inlet to 28.6%, see Figure 4. Results show 2% recombination inside the nozzle. In addition, the exiting X_H at 10 psia is higher at 3200 K than at 3000 K which reduces the average molecular weight.

Nozzle Contour Sensitivity

Based on the TDK capabilities, practical changes in the nozzle geometry showed minimal effects on Isp due to dissociation/recombination. The one-dimensional variations of pressure, temperature, and X_H throughout the LPNTP nozzle are displayed in Figures 5 and 6. Both figures show most recombination occurring around the throat. The change in X_H throughout the nozzle is very similar to changes in pressure. At the point were recombination stops, the pressure and flow density is close to zero.

Kinetics Sensitivity

The effects of hydrogen kinetic reaction rate uncertainty was also analyzed. Although differences in reaction rate coefficients should not affect the results of a comparative study such as this, it will be an important aspect in ensuring TDK accuracy and Isp predictions. Previously shown in Table 1 were three different sets of k_H and k_{H2} equations. Results show a small difference in ODK Isp between the three sets of k_H and k_{H2} equations. Each set of equations was determined from experimental reaction rates. The uncertainty for each set of k_H and k_{H2} equations is due to either scatter in experimental data or experiment type. At 10 psia, uncertainty in the C&W k_H and k_{H2} equations varies the ODK Isp from 999 seconds to 1014 seconds at 3000 K, and 1056 seconds to 1085 seconds at 3200 K.

CONCLUSIONS

TDK Isp is close to equilibrium flow at high Po and close to frozen flow at low Po. With To at 3000 K, the maximum TDK Isp and maximum difference between ODK Isp and ODF Isp occurs at Po ~100 psia, due to increased monatomic hydrogen recombination. The Isp is ~15 seconds higher at a Po of 100 psia than at 1000 psia. The optimum Po indicates a greater impact on Isp from recombination than from lower average molecular weights. A To of 3200 K increases both the amount of hydrogen dissociation (decrease in the average hydrogen molecular weight) and recombination. These characteristics boost the Isp above the value that would be obtained by only considering temperature effects.

Examination of various nozzle geometries showed a minimum impact on recombination and Isp. The significant changes that did occur were related to a more efficient use of two-dimensional nozzle flow. Most recombination occurs around the nozzle throat due to low static temperatures which foster recombination. Low static pressures and flow densities limit the amount of recombination downstream of the throat.

Finally, the uncertainty of the k_H and k_{H2}, at high To, has a significant impact on the Isp predictions. There is a large difference between ODE and ODF Isp's at a lower Po, and the ODK Isp could be anywhere between depending on the assumed reaction rate. The slow k_H and k_{H2} used in this study cause the ODK Isp to approach the ODF Isp at low static pressures.

RECOMMENDATIONS

Since the LPNTP Isp predictions were closer to frozen flow Isp than ideal equilibrium Isp at low Po, more extensive calculations using a TDK model that accounts for boundary layer effects, and non-adiabatic flow are not recommended at this time.

Faster kinetic reaction rates will increase both the monatomic hydrogen recombination and the Isp. Because there is an uncertainty with the high temperature values of k_H and k_{H2}, accurate hydrogen dissociation/recombination bench tests are recommended to determine if the actual reaction rates are different than the published reaction rates used in this study. High temperature sub-scaled nozzle tests with thrust and mass flow sensors are recommended to determine the actual Isp, because actual nozzle flow characteristics (e.g., boundary layer effects) might affect the amount of hydrogen dissociation/recombination.

Based on the results of this study, the chamber pressure recommended is 190 psia for a 3000 K chamber temperature. This chamber pressure is above hydrogen's critical pressure (188 psia) to minimize two-phase flow problems in the feed system (e.g., flow oscillations). Operating at 190 psia has an Isp slightly less than at 100 psia, but produces a higher thrust than at 10 psia and has a higher Isp than at 1000 psia. In addition, the nozzle should have a bell diverging section to shorten the nozzle length and minimize divergence losses. The nozzle's converging/throat section should be designed to maximize the recombination.

Finally, TDK only uses conical converging nozzle sections. Other kinetic computer models which can vary the converging nozzle contour should be investigated to determine the effects on Isp.

REFERENCES

1. Benton, D.: "CREST" computer program, version 4, 1988.

2. Nickerson, G.R., Coats, D.E., Dang, A.L., Dunn, S.S., and Kehtarnavaz, H.: "Two-Dimensional Kinetics (TDK) Nozzle Performance Computer Program." Software and Engineering Associated, Inc., NAS8-36863, March, 1989.

3. Cohen, N., and Westberg, K.: "Chemical Kinetic Data Sheets for High Temperature Chemical Reactions." J Phys Chem. Ref Data, 12, No. 3, 531-590, 1983.

4. Oldenborg, R.: "Hypersonic Combustion Kinetics - Status Report of the Rate Constant Committee, NASP High-Speed Propulsion Technology Team." NASP Tech Memo 1107, May, 1990.