Nozzle Flow in a Laser-Heated Hydrogen Rocket

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Abstract

THIS paper presents an analytical model of the nozzle flow in a hydrogen rocket whose power source is a 10.6-μm CW laser. The flow of hydrogen and the laser beam are parallel into a coverging-diverging nozzle. The hydrogen is in chemical equilibrium, absorbs the laser energy by inverse Bremsstrahlung, and loses energy by radiation. Estimates of convective heat losses are made using a hydrogen boundary-layer analysis. An upper limit to the specific impulse is obtained by expanding the flow isentropically from the throat to the exhaust pressure. For laser powers of 10 kW to 5 MW, these specific impulses vary from 1400 to 2400 s for 1-atm exhaust and from 4300 to 4700 s for vacuum exhaust. Radiative losses vary from 3.5 to 20%, though the maximum radiative energy flux to the walls ranges from 2 to 75 kW/cm^2. The convective loss estimates indicate that the gas flow will cool considerably in a 10-kW engine, but not in a 5-MW engine.

Contents

The laser-heated rocket is one concept for providing high specific impulse for space propulsion. A CW laser beam provides the energy source to heat a working fluid, which then expands through a nozzle, producing thrust in the usual manner. The attractive advantages include a remote energy source that is not part of the mass to be propelled; a heating mechanism that can reach much higher temperatures than those of a combustion process, with the possibility of higher specific impulse; use of a low-molecular-weight working fluid with high propulsive efficiency.

The operation of such a rocket depends on an efficient method for absorbing the laser energy into the gas and efficient conversion of the resulting high-energy gas into a high-speed flow. There are a number of possible absorption mechanisms, depending on the laser wavelength/working fluid combination used. Possible energy losses include radiative and convective heat transfer from the hot gas, and "frozen flow" losses of energy tied up in internal degrees of freedom of the exhaust gas.

To explore the fluid mechanics of such a rocket, one combination of wavelength and working fluid was chosen, namely, 10.6 μm (CO_2 laser) and hydrogen. The absorption mechanism is then inverse Bremsstrahlung, which requires collisions between electrons and neutrals or electrons and ions. Producing electrons in hydrogen requires temperatures of over 10,000 K. To heat the incoming cold hydrogen to this temperature so that it can produce electrons and absorb energy, a laser-supported-combustion (LSC) wave is postulated at the entrance to the "heating chamber." This wave heats the oncoming cold hydrogen by conduction and radiation from the hot gas behind the wave. (See Fig. 1.)

A quasi-one-dimensional-flow computer model was constructed to describe the flow and heating of hydrogen absorbing 10.6-μm radiation. The equations of motion include the mass, inviscid momentum, and energy conservation equations. The latter balances convection of total enthalpy, absorption of laser energy, and radiative losses. The laser power is found by balancing its absorption in the gas with the rate of decrease of power in the beam.

The equations are integrated by a method that uses the flow velocity as a specified function of x and solves for the nozzle shape. This avoids the singularity at Mach number unity, which arises when the nozzle shape is specified.

The gas properties that must be specified are the thermal and caloric equations of state, the absorption coefficient, and the radiation emission. The details of the models used are described in Ref. 1. Briefly, the thermodynamics of hydrogen in equilibrium is modeled as a mixture of molecules, atoms, singly charged ions, and electrons. However, below 8000 K, ionization is ignored, so only molecules and atoms are present. Above 8000 K, the hydrogen is assumed to be completely dissociated, so only atoms, ions, and electrons are present. The absorption coefficient is taken from the studies reported in Ref. 2 for inverse Bremsstrahlung absorption of 10.6-μm radiation by hydrogen. It includes an electron-neutral contribution proportional to the product of the electron and atom densities, and an electron-ion contribution proportional to the product of the electron and ion densities. The radiation emission is based on analysis performed in Ref.

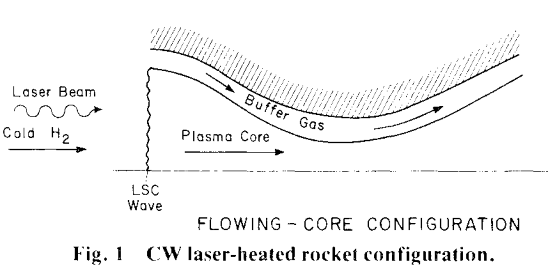

Fig. 1 CW laser-heated rocket configuration.

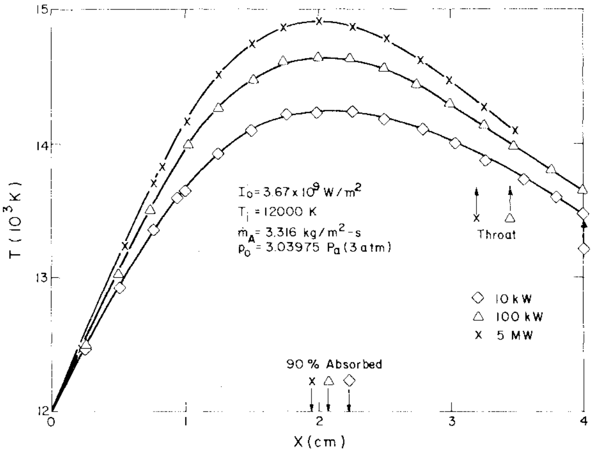

Fig. 2 Laser-heated streamtube temperature distribution.

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Index categories: Electric and Advanced Space Propulsion; Nozzle and Channel Flow; Radiatively Coupled Flows and Heat Transfer.

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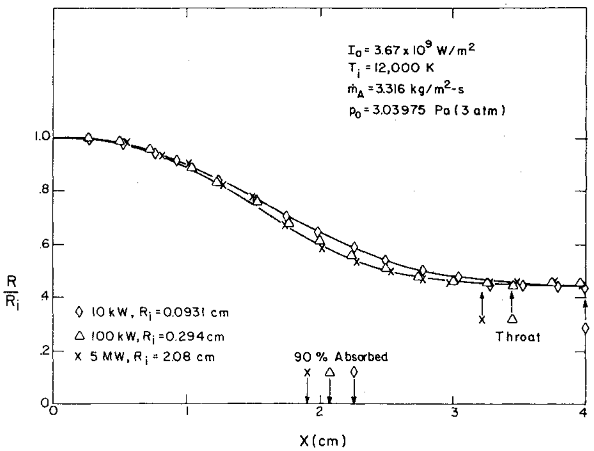

Fig. 3 Laser-heated streamtube radius distribution.

3 and summarized in Ref. 1. It is obtained by using the volumetric radiation loss from a gas cylinder in the optically thin regime, parameterized in a form suggested by semiclassical continuum radiation. The optically thick radiation was assumed not to affect the volumetric loss term, but only the details of the radial temperature profile at the edge of the hot gas, which was not considered in the present study.

The integration of the governing differential equations was begun at the back of the LSC wave, where the temperature T_i was taken to be 12,000 K. The power flowing in the gas at this temperature was subtracted from the incident laser power to conserve energy. The mass flow per unit area through an LSC wave $\dot{m}_A$ is related to the laser intensity I_0, which supports the wave, but this relation was not known when the present study was carried out. For this study a rough estimate was made of the mass flow for the intensity of interest.‡ The integration was stopped when the throat of the nozzle was reached.

The basic input parameters to the calculation are the laser power P, the incoming gas pressure p_0 and temperature T_0, the inlet area of the nozzle, and the gas mass flow rate. Six cases were calculated, comprising $P = 10,100$ and 5000 kW at $p_0 = 3 \times 10^5$ and 10^6 Pa (3 and 10 atm). The laser intensity was 3.67×10^6 kW/m^2 in all cases, with the mass flow rate at 9×10^{-5} kg/s for $P = 10$ kW, and proportional to P.

Typical results for the lower pressure are shown in Figs. 2 and 3, where the temperature and nozzle radius distributions are given. The peak temperature rises to between 14,000 and 15,000 K, depending on P, while the nozzle radius decreases slowly to 0.4 of its entrance radius at the throat, with very little effect of laser power.

‡A more recent study,[4] has explored LSC waves in hydrogen in some detail.

The high temperatures reached are caused by the necessity of using inverse Bremsstrahlung as the absorption mechanism and so requiring ionized H_2 to be present when absorption of the laser energy begins. Absorption then starts near 10,000 K and heats the gas from there. One consequence of the high-temperature operation is large radiant energy loss. The peak fluxes vary from 2 to 11 kW/cm^2 about 1.5 cm from the 12,000-K point. A second consequence is a large convective energy loss. A hydrogen boundary-layer calculation was made using the gas conditions shown in Fig. 2 as freestream. The peak heat flux to a 1300-K wall was 34 kW/cm^2 at the throat. However, the total heat flux was such a large fraction of the laser power that such an uncoupled calculation is not realistic. But it clearly indicates high heating rates from which the walls must be protected.

On the other hand, the high temperature level does bring with it the possibility of high specific impulse. As an upper limit, one may take the enthalpy flux at the throat and convert it all to velocity to obtain the ideal I_{sp} for vacuum exhaust of H_2 molecules at 0 K. This value ranges between 4300 and 4700 s, compared to less than 500 s for the best chemical rocket. Since a useful range for space propulsion is probably 1000-1500 s, there is plenty of leeway for introduction of losses in the expanding part of the nozzle while maintaining a usefully high I_{sp}.

The principal conclusions from this study are

1) CW laser heating of H_2 by 10.6-μm radiation leads to the potential of very high I_{sp}.

2) The temperatures reached produce considerable radiative and convective losses, which pose a difficult heat protection problem for the nozzle walls.

3) To alleviate this heat protection problem, several methods should be explored. One is the use of a laser wavelength/propellant gas combination, which allows absorption at a somewhat lower temperature. A second is the use of a buffer gas near the walls to absorb some of the heat from the laser-heated gas and contribute to the thrust.

Acknowledgments

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