Measurement of Detonation Propulsion in Helium and Performance Calculations

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Results of detonation propulsion are extended to helium as the ambient gas to help in the assessment of performance in the atmospheres of the major planets. Measurements confirm benefits derived from detonating propellant over conventional chemical rocket propulsion. Benefits, however, are reduced at high pressures in a low molecular weight gas. Numerical calculations by means of a monodimensional hydrodynamic code follow the different trends obtained experimentally for high and low molecular weight gases and also offer new insights on the time behavior of the process.

Nomenclature

a_0 = speed of sound in ambient gas
e_α = specific energy released in explosion
F = thrust
g_c = conversion constant
I_{sp} = specific impulse
$I_{sp}(t)$ = transient specific impulse
L = nozzle length
m_a = mass of ambient gas contained in nozzle
m_e = mass of explosive
P_0 = ambient pressure
R = universal gas constant
T_0 = ambient temperature
t = time
γ = specific heat ratio
θ = nozzle half angle
μ = molecular weight
ρ_0 = density of ambient gas
σ = mass ratio m_a/m_e

Introduction

RECENTLY, there has been an interest in developing a propulsion system for high-pressure environments based on chemical detonation rather than deflagration.[1,2] The advantage of this concept is that in high-pressure environments a larger specific impulse is obtainable from explosives than from conventional chemical propellants. This derives from the very high reaction pressures generated by detonating propellants which correspond to very large expansion ratios of rocket nozzles. Conventional chemical rockets, because of material strength limitations in the combustion chamber, operate at very inefficient expansion ratios in a high-pressure environment and therefore produce low specific impulse. Back and Varsi[2] gave an experimental demonstration and a simplified analytical explanation of the principles involved in detonation propulsion.

This paper reports new experimental results obtained by measuring the specific impulse in helium ambient gas to assess the performance in the atmospheres of the major planets. A comparison with monodimensional hydrodynamic calculations provides further insights into application of the concept to planetary missions.

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Experiments

A new series of experiments was carried out with helium as the ambient gas at pressures ranging from 1 to 69 bars and at a temperature of 25°C. Previous experiments were reported[1,2] with nitrogen and carbon dioxide as the ambient gases. In this study helium was selected to evaluate the performance in a relatively low molecular weight gas atmosphere typical of the outer planets such as Jupiter and Saturn.[3,4] Although the primary constituent in the atmospehres of the outer planets is believed to be hydrogen with a smaller percentage of helium, tests with helium are simpler to carry out because of safety considerations and should reveal the performance trend in low molecular weight gases. An approximate analytical investigation of detonation propulsion[2,5] indicated a reduced specific impulse with lower molecular weight gases. Details are given in Ref. 2.

The experimental system is shown in Fig. 1. A conical aluminum nozzle was mounted on a sled that was free to move vertically. A small amount of explosive "deta-sheet" placed at the nozzle end wall was detonated by a microdetonator. The travel of the sled was measured, and from this the specific impulse was obtained as discussed in Ref. 2. The whole system was placed in a tank filled with the desired gas at pressures up to 69 bars.

The specific impulse is obtained as a ratio of the total impulse to the total mass of explosive: the disks of "deta-sheet" and the charge in the microdetonator. The portion of total impulse generated by the ejecting of the inert materials in the detonator and lead wires was determined by comparing experimental runs using one, two, and three detonators operated simultaneously to fire the main charge of "deta-sheet." The results showed that about 5% of the specific impulse as presented in this paper is attributable to these inert materials. In a separate series of experiments with nitrogen at various pressures overall reproducibility was tested and found to be within 1% to 2% before permanent deformation occurs in the firing plug.

The results of the experiments reported in Table 1 and displayed in Fig. 2 revealed an unexpected phenomenon. Although the specific impulse was still higher than that of conventional chemical rockets used for comparison and operating in the same high pressure, the specific impulse in helium decreased as the pressure increased. This trend is contrary to the previous experimental results with nitrogen and carbon dioxide and was not indicated by the previous approximate analysis for the situation where the mass of ambient gas in the nozzle was much greater than the mass of gas produced in the explosion, i.e., where $\sigma = m_a/m_e$ is much

Table 1 Helium experimental data

Run no.	Nozzle		σ	Ambient gas			Specific impulse, I_{sp}, sec[a]
	Half-angle, deg	Length, cm		Pressure, bars	Temperature, °C	Density, g/cm^3	
K.1	10	15.9	0.035	1	25	1.69×10^{-4}	223
K.2	10	15.9	0.30	8.5	25	1.44×10^{-3}	211
K.3	10	15.9	1.80	51.0	25	8.63×10^{-3}	192
K.4	10	15.9	2.11	59.5	25	1.01×10^{-2}	182

[a] Units of specific impulse are lbf-sec/lbm. For conversion to the SI system (N-sec/kg), the tabulated values are to be multiplied by the factor 9.806.

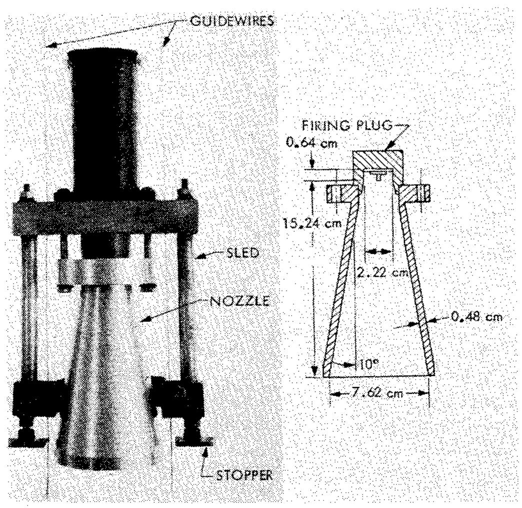

Fig. 1 Experimental device.

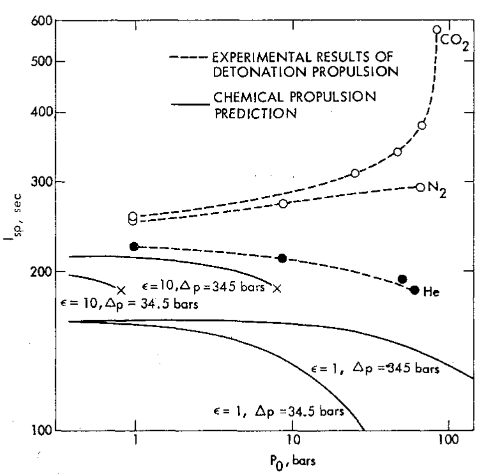

Fig. 2 Detonation propulsion results and chemical propulsion predictions.

greater than unity. For the present results with helium values of σ are relatively small (Table 1).

For comparison the performance of an anhydrous hydrazine engine is shown in Fig. 2 for a combustion temperature of 1000 K.[2] Computations were made at two nozzle expansion area ratios ε and two chamber to ambient pressure differences Δp. The crosses denote the maximum ambient pressure before shock-induced flow separation would occur in the nozzle, thus limiting the utilization of larger expansion area ratio nozzles which have better performance.

One-Dimensional Analysis

In order to interpret the experimental data, a numerical analysis was performed. The blast wave following the detonation of the propellant was treated with a one-dimensional hydrodynamic code, and the flow in the exhaust plume was taken to be confined in an imaginary cone extending from the nozzle to infinity. Perfect gas law was used

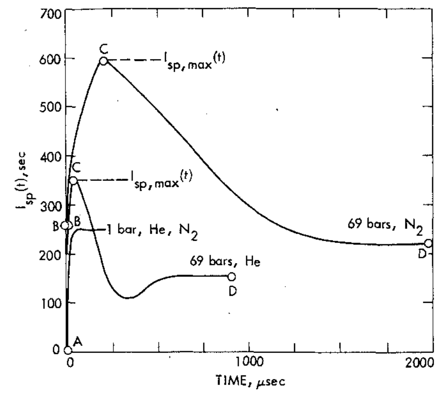

Fig. 3 Calculated transient specific impulse.

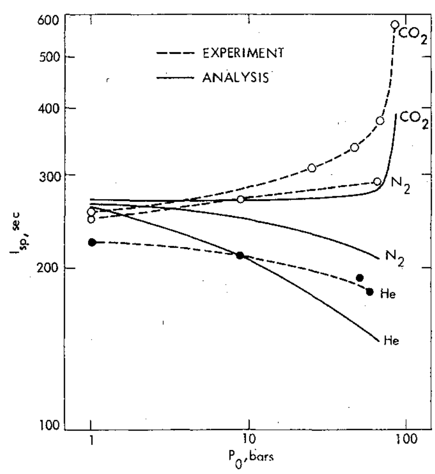

Fig. 4 Comparison between experimental and analysis.

for the ambient gas and the JWL equation of state for the product gases.[6] The volume burn assumption used in the calculations is believed to be reasonable because the layer of "deta-sheet" that covered the end wall was relatively thin. The one-dimensional Lagrangian hydrodynamic code which integrates the three conservation equations is similar to the one developed by Wilkins.[7] Wall effects were neglected.

Figure 3 illustrates typical results of the calcualtion. It is noted that the mass of the explosive was 1.53 g, and the specific heat of explosion was 1100 cal/g for the He case and 1180 cal/g for the other ambient gases. The transient specific impulse

$$I_{sp}(t) = \int_0^t F\, dt/m_e g_c$$

for helium and nitrogen at 1 and 69 bars are plotted with respect to time. Three portions of the predictions are recognizable and are indicated on the 69-bar helium curve. The first portion AB, which amounts to about +250 sec of $I_{sp}(t)$, represents the impulse generated mainly by the expansion of the explosion products. The second portion BC, which amounts to +100 sec, represents the contribution of the ambient gas inside the nozzle which is being exhausted by

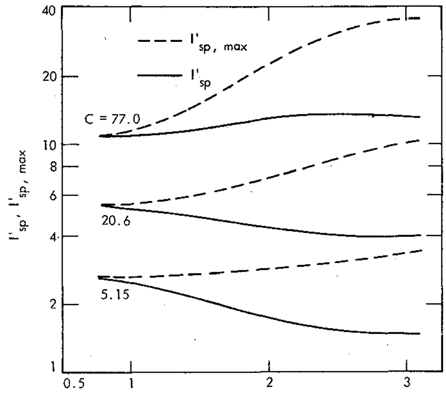

Fig. 5 Nondimensional specific impulse, $\gamma = 5/3$.

the blast wave energy. Finally, the third portion CD, which amounts to about -200 sec, is due to the partial vacuum (underpressure) generated by the ambient gas which is overdriven, leaving a rarefraction inside the nozzle.

The magnitude of the first portion AB was deduced by observing that, in the limit of zero ambient pressure, the only contribution to the impulse is that of the products of detonation as approximately shown by the helium or nitrogen 1-bar curve in the figure. The final specific impulse,

$$I_{sp} = \int_0^\infty F \, dt / m_e g_c$$

is 145 sec. The magnitude of the last two components increases with pressure.

Inspection of Fig. 3 indicates the rather large magnitude of the calculated specific impulse degradation associated with underpressure, portion CD of the curve, for both helium and nitrogen at higher ambient pressure. The magnitude of this degradation is of the order of the final specific impulse, being about one-half the peak specific impulse. This rarefaction effect also was predicted by the earlier approximate analysis,[2,5] and the present calculations substantiate this trend.

Furthermore there are differences in the behaviors predicted for He and N_2 as shown in Fig. 3. First, the portion BC of the curve representing the contribution of the ambient gas is smaller than the underpressure portion CD for helium, whereas these portions are nearly the same with nitrogen. Second, for helium, there is an oscillation in the portion CD which is not predicted for nitrogen. The first of these observations indicates that the contribution to the specific impulse obtained from ambient helium is negative. The same trend is predicted for nitrogen although the negative contribution to the specific impulse is not as large.

The extent to which this predicted behavior occurs is difficult to ascertain since only the final specific impulse is measured. Figure 4 shows the comparison between the measurements and the numerical calculations. Although there is as much as 30% discrepancy between them, the calculations nevertheless approximate the data and indicate trends to some degree. There are, however, differences over the pressure range investigated. At lower ambient pressures the predictions are above the data, whereas at higher ambient pressures they tend to be lower than the data. The discrepancies at higher ambient pressures are believed to be associated with the inability of the one-dimensional calculations to handle the plume expansion and the refilling of gas in the nozzle during the underpressure phase. The calculated impulse loss during the rarefaction phase may be too large and thus the predicted specific impulse is reduced too much below its peak values. Clearly, two-dimensional calculations are needed to resolve these uncertainties. However, the one-dimensional calculations do provide useful information which was not available before, such as on the reduction in specific impulse with increasing ambient pressure in relatively low molecular weight gases.

The results of various calculations performed with the one-dimensional hydrodynamic code are displayed in Fig. 5 in a compact form, by means of four nondimensional groups of variables. The figure is drawn for ambient gases with a specific heat ratio of $\gamma = 5/3$. The final specific impulse I_{sp} and the maximum specific impulse $I_{sp,\max}$ are expressed in nondimensional form by dividing them by the speed of sound a_0 of the ambient gas, as follows:

$$I_{sp}(g_c/a_0) = I'_{sp}$$

and

$$I_{sp,\max}(g_c/a_0) = I'_{sp,\max}$$

respectively. The energy-related nondimensional group C is obtained by dividing the specific energy released in the explosion of the propellant by the specific internal energy of the ambient gas:

$$C = e_\alpha \rho_0 (\gamma - 1)/P_0 = e_\alpha (\gamma - 1) \mu / R T_0$$

Finally the geometric number D is the ratio of the nozzle length L to the characteristic blast wave length. (At this distance from a point source explosion the strength of the shock has decayed to approximately 1.5.)

$$D = [L^3 P_0 (1 - \cos\theta)/2 m_e e_\alpha]^{1/3}$$

The more prominent features of the figures are 1) progressive increase of the difference between the maximum and the final specific impulse with increasing ambient pressure at constant energy ratio; 2) progressive increase of the difference between the maximum and the final specific impulse with increasing energy ratio at constant ambient pressure; and 3) for sufficiently high values of the energy ratio it appears possible to obtain increasing final specific impulse values for increasing pressures. However, it should be recognized that the difference between the maximum and the final specific impulse depends on the refilling phase and is probably the portion of the process which is the least accurately computed by the one-dimensional code.

Conclusions

The measurements of performance of detonation propulsion in helium gas confirm the benefits over conventional chemical rockets demonstrated earlier for other gases. This finding suggests that the exploration of the major planets with low molecular weight atmospheres would be facilitated by application of this mode of propulsion to the probing spacecrafts. Current models of the Jupiter atmosphere place the molecular weight at about 2.3. Furthermore, the indication of increasing difference between maximum and final specific impulse with increasing pressure, particularly in low molecular weight places added emphasis on the effort to design a system capable of offsetting the negative contribution of the refilling phase by redirecting the gas flow by either active or passive devices.

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