Fuel Regression Rate in a Paraffin-HTPB Nitrous Oxide Hybrid Rocket

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Abstract

A series of paraffin-HTPB based nitrous oxide hybrid rocket fuels have been studied experimentally in a laboratory-scale motor. The novel nitrous oxide feeding system and injector are developed to inject oxidizer into rocket combustion chamber and promote the proper mixing of fuel vapour and oxidizer to form the combustible mixture. Results of internal ballistics analysis of N_2O hybrid rocket indicated that the same regression rate is at same level as swirling gaseous oxygen, but lower in specific impulse. The firing tests are performed successfully and the performance is also better than the literature results. These experimental findings indicate that results of N_2O hybrid rocket with 50P paraffin-based fuel provide the fatal database to design the propulsion system of standalone launch vehicles for academic purpose.

1 Introduction

The hybrid rocket is kind of green and safe propulsion system. A little bit lower performance as compared to solid rocket, hybrid rocket motor was however, finally chosen as the engine to fly SpaceShipOne to win the Ansari X Prize for the superiority of its low-cost and high-reliability. The success of SS1 could increase general interest in hybrid engines. Classical hybrid rockets have suffered from slow solid-fuel regression rates and relatively poor combustion efficiency.

The complete modeling of hybrid motor combustion is quite complicated due to various physical and chemical processes. The model has to consider in a fuel grain passage a reacting flow created by the two distinctly different fluids: one, the mostly-vaporized- oxidizer entering the fore end of the fuel grain passage and the other, the fuel vapor blowing from the passage-wall. The boundary layer growing from the fore end of the passage contains the diffusion flame front within. Fuel is vaporized as a result of heat transferred from the flame front to the fuel surface. The fuel vapour converts towards the flame front while the oxidizer from the free stream diffuses into the boundary also towards the flame front from the opposite direction. Thus, the limit on regression rate for the conventional hybrid combustion configuration is set by the physical phenomena of heat and mass transfer from the relatively remote flame zone to the fuel surface. The hybrid rocket performance is limited by these above aero-thermo-chemical driving mechanisms.

Classical hybrid rockets have not yet found however, widespread use for either commercial or military applications, possibly because they suffer from slow fuel regression rates, low volumetric loading, and relatively poor combustion efficiency. To achieve the necessary mass flow rate of pyrolyzed vapor from the fuel grain to produce the desired thrust level, complex cross sectional geometries with large wetted surface are must be employed. Normally, the regression rates of modern hybrids that utilize polymers as the fuel are much lower than conventional solid-rocket burning rates.

Various methods for increasing fuel regression rates have been suggested in the past. The addition of ammonium perchlorate (AP) and/or aluminum in HTPB fuel is able to enhance the regression enhance rate at high GOx mass flux conditions. A vortex hybrid engine having the capability of generating coaxial, co-swirling, counter flowing vortex combustion field designed by Knuth et.al [1]. Tremendous enhancement of fuel regression rates was obtained up to 650% larger than those in similar classical hybrids. By employing swirling GOx injection technique, Lee [5] demonstrated 50% regression rate and 30% Isp (specific impulse) increases as compared to non-swirling one in a HTPB/GOx hybrid motor system. Increased regression rates by several hundred percent have been observed with solid cryogenic hybrids including several frozen organic liquids and normal pentane [2]. The regression-rate model for these liquefying fuels has been developed by Karabeyoglu[2]. Very high regression rates observed in the cryogenic tests have been successfully predicted by this liquid layer theory which also led to the conclusion that paraffin waxes will exhibit high regression rates comparable to pentane.

The mixture of 50% paraffin wax and 50% HTPB (so-called 50P fuel) presented the best performance among all test fuels in the previous study [5-8]. About 185% and 105% regression rates increased by burning with paraffin wax and 50P fuels respectively, as compared to regression rates of HTPB-swirling O2 hybrid system at GOx=90kg/m^{2}sec. In order to enhance the fuel and oxidizer mixing level inside the motor, all tests were carried out with swirling GOx injection technique. Specific impulse of 50P fuel can reach up to 220 sec as GOx=110 kg/m^{2}sec. Property of lower regression rate of HTPB fuel resulted in a lower Isp value and presenting fuel-lean combustion as GOx went beyond 80 due to cause part of oxygen ejecting through nozzle directly but without reacting with fuel vapor. These experimental findings indicate that paraffin-based fuel provides the opportunity to satisfy a broad range of mission requirements for the next generation of hybrid rockets. This experimental finding indicates that a better performance of a hybrid rocket can be obtained by burning a proper fuel.

The popular oxidizer adopted for hybrid rocket propulsion system includes liquid oxygen (LOX), gaseous oxygen (GOX),

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nitrous oxide (N2O), hydrogen peroxide (H2O2), HTP (Hight_test Peroxide) and NTO (N2O4). The LOX is the main oxidizer for the large-scale liquid or hybrid rocket propulsion, and GOX is easy to use and apply to investigate the lab-sacle hybrid rocket propulsion characteristics.

N2O possesses many advantages over other oxidizers, that it is colorless, non-toxic, stable, non-explosive, and non-flammable at room temperatures. And it is easy to store and safe for low-cost propulsion system due to the chemical composition (36.3% O2 and 63.7% N2) akin to those of air, self-pressurizing characteristics with high vapour pressure at 52 bar (at 20 ^oC) to satisfy the mission requirements with single simple storage tank. The American Rocket Company (AMROC) even demonstrated hybrid rocket system with nitrous oxide as its oxidizer [1] and SpaceShipOne ship also used it for propulsion in their successful space flight prize competition. N2O for propulsion system is versatile, for example for monopropellant in satellite attitude control, rocket ignition system and bipropellant or hybrid rockets. No matter how to apply N2O in the propulsion system, the emergent need to utilize it to provide the oxygen is that the N2O should be decompose to release the oxygen and heat by external energy or proper catalyst. N2O could decompose exothermically with adiabatic decomposition temperature reaching 1640^{o}C and decomposed oxygen could supply to meet the further combustion needs for a variety of fuels. NASA had demonstrated the large-scale paraffin fuel hybrid rocket firing test with N2O as oxidizer and the results indicated that the regression rate and combustion rate in the same trend and consistent with the cases by using gaseous oxidizer (GOX).

A series of paraffin-based hybrid rocket fuels were tested successfully in the laboratory-scale motor that was designed similar to the classical one with an aft-mixing chamber in the previous study [5-8]. Fuel regression rate and specific impulse were selected as the indicators for the performance of the developed hybrid rocket fuel. Data reduction methods to analyse the internal ballistics of a hybrid rocket has been developed to investigate and examine the factors influencing the performance of a hybrid rocket by the measured data. Based on our successful fuel grain casting technique and GOX hybrid rocket tests, the standalone self-supply rocket propulsion application should be developed for propulsion system of future academic launch vehicle. The N2O is selected as the candidate oxidizer for the further launch application and the performance of the N2O hybrid rocket will be investigated in the present study.

2 Experimental Set-up

2.1 Fuel grain specimen

Paraffin wax and HTPB were selected as the solid fuel in the present study. Paraffin is an odorless, tasteless, waxy solid. It melts between 47°C and 65°C and is unaffected by most common chemical reagents but burns readily in air. Chemically, paraffin is a mixture of high molecular weight alkanes with the general formula, where n is an integer between 22 and 27. HTPB (Hydroxyl-terminated Polybutadiene) cross-linked with isophorone diisocyanate, IPDI has widely been used as the solid fuel for hybrid rocket motors.

The mixture of 50% paraffin wax and 50% HTPB fuel (so-called 50P fuel) presented the best performance among all test fuels [6-8]. This mixture was then selected as the fuel for the following testing. Weight ratios of 50% paraffin and 50% HTPB fuel grain was prepared by mixing liquefied paraffin with HTPB/ IPDI(92/8) mixture at 80^{o}C. This mixture was then poured into cylindrical motor equipped with a casting mode for the grain configuration. With the proper curing process as carried out for HTPB grain, the casted fuel grain, 41mm diameter*180mm length, is ready for firing test. The grain configuration, as shown in Fig. 1 in the present study. The specific weight of the test grain is 0.91.

2.2 Test equipment

The hybrid rocket test facility consists of N2O feed system, N2 purge, pyrogen ignition and thrust measuring systems. Nitrogen is employed as purge gas to terminate combustion after the desired burning time. Propane gas and a spark formed the pyrogen igniter to initiate the test. Hybrid rocket thrust is measured by a flexure plate type thrust stand, in which hanged horses design and placed pneumatic control devices on the stand are employed. The natural frequency of the thrust stand measured is 8Hz. The operating pressure of the motor was controlled using interchangeable graphite exit nozzle.

The nitrous oxide (N2O) feed system is composed of feed pipelines, control valves and oxidizer tank. The tank pressure is initially at the N2O vapour pressure 56.6 bar (at 25 ^oC). As the experiment proceeded, the tank pressure and weight of N2O tank are monitored and recorded for analysis. The liquid N2O is supplied through the pipelines and atomized through the oxidizer injector to provide proper oxidizer supply angle and the N2O vapour into the hybrid combustion chamber. Once the ignition gas heated up the combustion chamber, the N2O will decompose into oxygen and nitrogen to sustain the further combustion.

2.3 Experimental procedure

The nitrous oxide regulator located at upstream of the Venturi was first adjusted to supply the desired oxidizer mass flow rate during tests. The pyrogen igniter was initiated and maintained for about 1 second. Immediately after turning off the ignition system, the pneumatic control valve was actuated to supply the oxygen. After the desired burning time, in quick successions oxidizer supply was cut off and nitrogen purge was opened to extinguish combustion. The test measurements were the thrust and chamber pressure and pressure at upstream and the throat of Venturi. All of the signals from stain-gauge type, pressure transducers and oxygen temperature were recorded by LabView system. The sampling rate was 1000 samples/s. Other pre-and post- test measurements were the initial and final nozzle throat diameters and grain mass and dimension. For each test, the desired N2O mass flow rate could be obtained by measured data.

3 Results and Discussions

Several firing tests using nitrous oxide (N2O) as oxidizer were carried out successfully from July to Aug. 2008. The primary observed variables in the test were the time histories of chamber pressure and thrust, fuel consumed and oxidizer mass flow rate etc. The reduction method has been developed in the previous study. Specific impulse was evaluated based on actual burning time, and fuel regression rate was calculated based on space-time-averaged scheme [6-8]. The averaged oxidizer mass flux GOx is estimated based on the average port radius. And the measured data were analyzed and the results and discussions are presented in the following paragraphs.

3.1 Effects of Nitrous Oxide as oxidizer

Figures 2 and 3. show N2O hybrid rocket testing pictures for two different nitrous oxide supplied rates at 368 and 248 kg/m^2sec respectively. Figure 2 indicated a long and relative narrow hot jet from the nozzle compared to the case in Fig. 3. And it is noteworthy that the hot jet observed in Fig. 2 was a little lifted off from the jet nozzle, and indicated the outside combustion behaviour observed.

The thrust and pressure time histories for these two cases are shown in figures 4 and 5 respectively. According to the values at figures, the case with higher oxidizer supply at 368 kg/m^2sec produces about 31 kg thrust and chamber pressure at 500 psi, the other at lower oxidizer mass flux are 14.5 kg thrust and 210 psi chamber pressure.

Basically, the fuel regression rate is the exponential function of oxidizer mass flux with one exponent for specific fuel composition as r=a*(OX)^n*. So, the higher oxidizer mass flux in Fig. 2 resulted in the higher fuel regression rate and much fuel from fuel grain was vaporized to mix with the oxidizer to form the combustible mixture.

The specific impulse and fuel regression rate are calculated and summarized in figures 6 and 7 respectively. The results shown are compared to those tests using gaseous oxygen with or without swirling injection mechanism. The pre-exponential factor and exponent of the regression rate correlation are listed in Table 1 compared to those results from literature [3]. The slope of regression rate in N2O hybrid rocket is gentler than the swirling GOX case, and at the almost same trend as the non-swirling GOX case by using the same fuel grain, but higher regression rate. The proper amount heat from ignition and succeeding combustion is needed to transfer to solid fuel grain surface for fuel heat-up and vaporization. Obviously, the cases with N2O and swirling GOX have better combustion conditions to provide the heat and results in better fuel regression rate.

As to the specific impulse, N2O hybrid rocket has lower values than the swirling GOX hybrid rocket by almost 10 %, and higher than the non-swirling GOX cases. The fuel and oxidizer mixing mechanism inside the rocket combustor to form combustible mixture is very important to obtain better combustion efficiency, thus better specific impulse. The decomposition condition of nitrous oxidizer is also fatal to the rocket performance and the time to decompose N2O is also determined by the aerothermochemical conditions inside the rocket combustion. Much amount of N2O supplied needs more time and energy to initiate the decomposition process, and result in the lower specific impulse and regression rate than the swirling GOX case.

3.2 Comparison with Different Fuel regression rate

Table 1 and Figure 7 also show the fuel regression rates from literature results [3] and [6] to demonstrate the N2O hybrid rocket performance in the present study. Literature [3] tested four different fuel compositions, HDPE, PMMA, HTPB, and Sorbitol with nitrous oxide as oxidizer, and the regression rate increases as the order number increases, indicating sorbitol fuel has best regression rate. The results also show that the candidate fuel 50P has best performance compared to the four fuels in literature [3] if swirling GOX, and N2O adopted and supplied oxidizer mass flux higher than 100 kg/m^2 sec. These tests in the present and previous studies had higher oxidizer mass supplied rates than the ref. [3] results and the power exponent in the regression correlation law also steeper than those in literature [3].

4 Conclusions

A series of paraffin-based nitrous oxide (N2O) hybrid rocket fuels have been studied experimentally in a laboratory-scale motor. Internal ballistics of a N2O hybrid rocket burning with 50% paraffin wax and 50% HTPB fuel (50P) has been investigated and analysed. The performance of N2O hybrid rocket is comparable to the GOX hybrid rocket with same level at fuel regression rate, but lower in specific impulse. The fuel regression rate correlation against oxidize mass flux is obtained and compared to literature results, could be ready for hybrid rocket launch vehicle design. Databases of these combustion characteristics and results inside the motor play an important role as a guideline to designing a high performance hybrid rocket and standalone launch vehicles for academic purpose.

5 Acknowledgments

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Table 1 Present N2O+50P regression rate coefficients compared with literature results [3,6]

Fuel	a*	n*
HDPE [3]	0.104	0.352
PMMA [3]	0.111	0.377
HTPB [3]	0.198	0.325
Sorbitol [3]	0.286	0.310
50P [S. GOX, 6]	0.026	0.8076
50P [NSGOX, 6]	0.011	0.8697
50P [N2O, present]	0.1146	0.5036

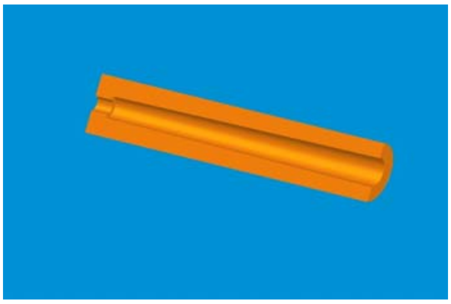

Fig.1 Solid fuel grain configuration

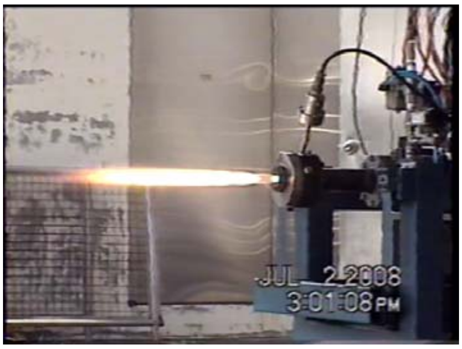

Fig.2 N2O Hybrid rocket testing (case no: R970702-02) at N2O mass flux 368 kg/m^2 sec.

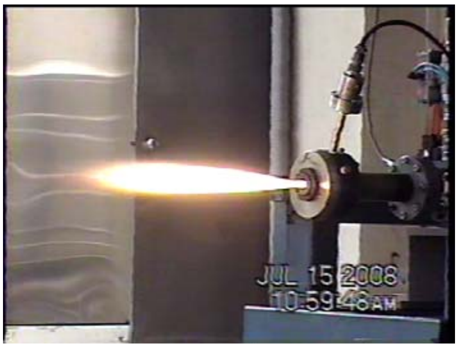

Fig.3 N2O Hybrid rocket testing (case no: R970715-04) at N2O mass flux 148 kg/m^2 sec.

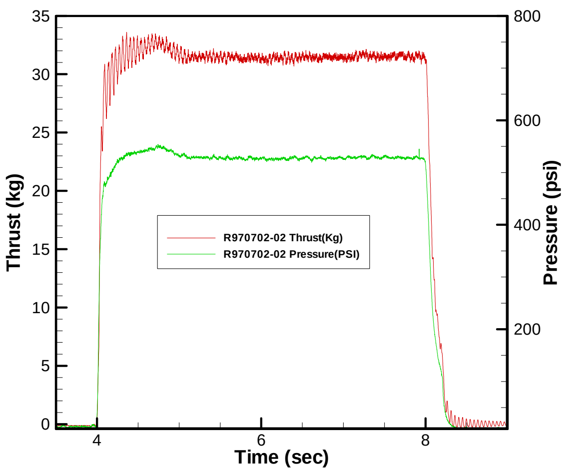

Fig.4 Thrust and Pressure time traces of test case R970702-02

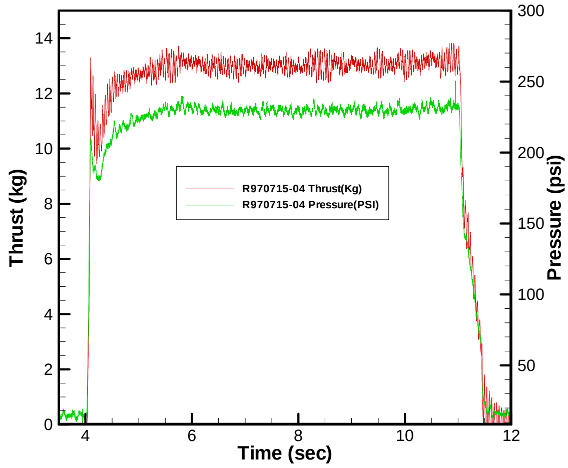

Fig.5 Thrust and Pressure time traces of test case R970715-04

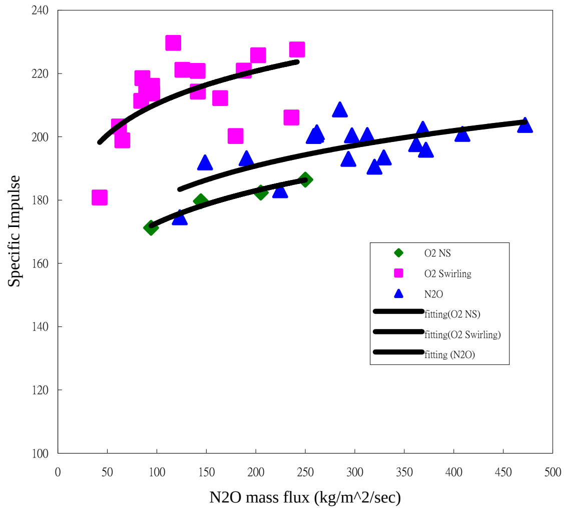

Fig.6 Comparison of gaseous oxygen and liquid N2O oxidizer mass flux on specific impulse of tested 50P fuels

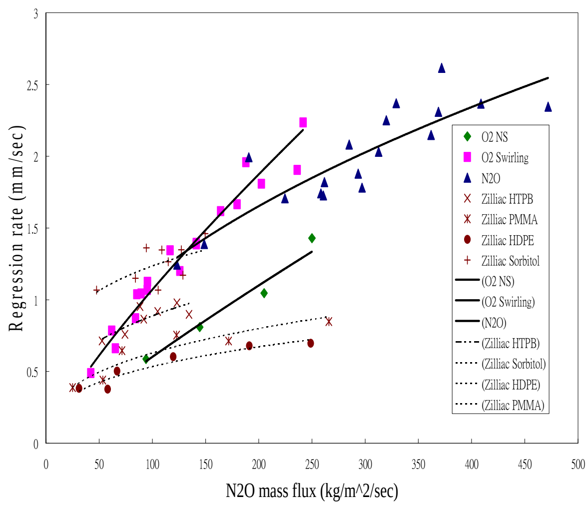

Fig.7 Comparison of gaseous oxygen and liquid N2O oxidizer mass flux on regression rate of tested 50P fuels