N_2O PROPULSION RESEARCH AT TSINGHUA: 2006

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ABSTRACT

Nitrous oxide propulsion gains attention after successful suborbital flights of SpaceShipOne space-plane propelled by N_2O/HTPB hybrid rocket motor in 2004. Due to its unique properties nitrous oxide can be used as a multi-purpose propellant on-board spacecraft. The research started at Tsinghua in 2002 covers several key-technology development areas of nitrous oxide propulsion including restartable monopropellant and hybrid rocket motor, as well as their storage and feed subsystems. This paper presents the up-to-date research experience promoting application of nitrous oxide for launcher as well as in-orbit propulsion. Based on this experience advanced multi-functional propulsion system featuring different types of thrusters using nitrous oxide can be developed for space applications.

1. INTRODUCTION

Nitrous oxide propulsion is presently getting growing attention in the world after successful suborbital flights of SpaceShipOne space-plane propelled by N_2O/HTPB hybrid rocket motor in 2004. [1] This is because application of nitrous oxide (N_2O) as a rocket propellant offers several advantages crucial for private space businesses. Environmental friendliness and non-toxicity of N_2O let private companies avoiding huge expenses associated with area decontamination and exposed personnel medical treatments in the cases of accidental propellant spills. The companies also save on personnel protective measures (clothing, etc.) since only minimum protection is required. [2] N_2O non-flammability and non-explosiveness reduce associated safety overheads. Most of the conventional fuel (HTPB, kerosene, etc.) combinations with nitrous oxide are non-hypergolic at normal temperatures so that they present no danger in the case of accidental contact of the propellants. Storability of nitrous oxide in the wide rage of temperatures not only eliminates the need in cryogenic facilities at the launch site but also alleviates the problems associated with propellant freezing or decomposing in storage tanks in orbit. [3]

N_2O has relatively high density (~745kg/m^3) that results in reasonable propellant tank sizes. Its vapor pressure (~51bar at 20°C) eliminates the need in propellant expulsion subsystem. Compatibility of nitrous oxide with common materials makes the choice of propulsion structural materials easier. The last two properties suggest application of new light and strong composite materials for N_2O storage tanks. Being a gas nitrous oxide can be used by cold-gas thrusters for spacecraft attitude control. Decomposed by catalyst N_2O can be used in mono- or bipropellant thrusters for station-keeping, orbit maneuvering, launch, and landing propulsion functions.

Recognizing the potential of nitrous oxide as a rocket propellant the research started at Tsinghua in 2002 covers several key-technology development areas including restartable monopropellant and hybrid rocket motor, as well as their storage and feed subsystems.

2. MONOPROPELLANT

The schematics of a nitrous oxide monopropellant thruster employing catalytic decomposition is shown in Figure 1.

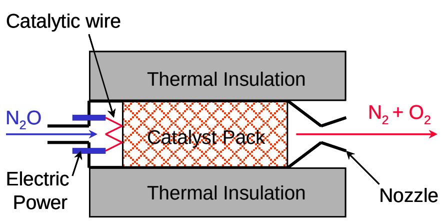

Figure 1. Nitrous oxide monopropellant thruster schematics.

In this device a flow of nitrous oxide is injected into the decomposition chamber. Upon injection, nitrous oxide starts to decompose on an electrically heated catalytic wire. The heat generated by decomposition activates the main catalyst, which in turn decomposes more nitrous oxide, and generates more heat. The process proceeds with increasing temperature until all

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of the catalyst is activated and the rate of decomposition reaches its maximum when steady state is achieved. The products of the decomposition leave the chamber through the nozzle producing thrust. Once balance between heat generation by decomposition and heat dissipation into surrounding is achieved the reaction becomes self-sustaining so that electrical power input is no longer required.
Figure 2 shows specific impulse performance for nitrous oxide monopropellant reaching its maximum (I_{sp}=206s) at about 1640°C.

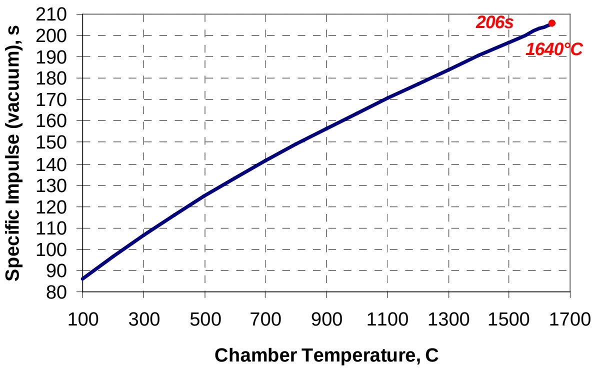

Figure 2. Theoretical specific impulse of nitrous oxide monopropellant thruster as a function of chamber temperature. (nozzle expansion ratio = 200)

More than 300 firings of N_2O monopropellant prototype have been accomplished to date. Figure 3 shows an example of typical N_2O monopropellant prototype thruster firing in a lab.
More than 50 different catalysts have been tested. A catalyst activation temperature as low as 250°C has been recorded. A catalyst lifetime in excess of 15 hours was demonstrated at 49 restarts. Nitrous oxide mass flow rates up to 1.1 gm/s have been supported. Decomposition temperatures in excess of 1500°C have been demonstrated.

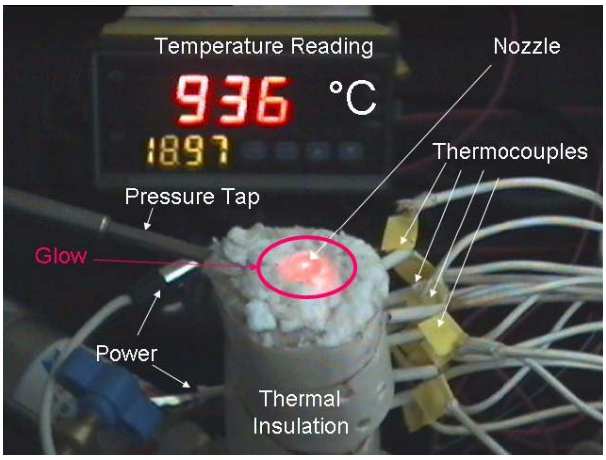

Figure 3. Nitrous oxide monopropellant firing. (The exhaust plume is invisible.)

During the research at Tsinghua N_2O decomposer design diameter and length have been reduced to 4 and 20mm respectively while it's mass to ~20gm (Figure 4 and Table 1) for 10-150mN thrust range. [4]
At present the N_2O monopropellant research focuses on reduction of thruster's start-up transient (from current 52s) and input power (from current 24-35W).

3. HYBRID ROCKET MOTOR

Hybrid rocket motor using nitrous oxide is capable of higher specific impulse performance (Figure 5) than the monopropellant thruster.

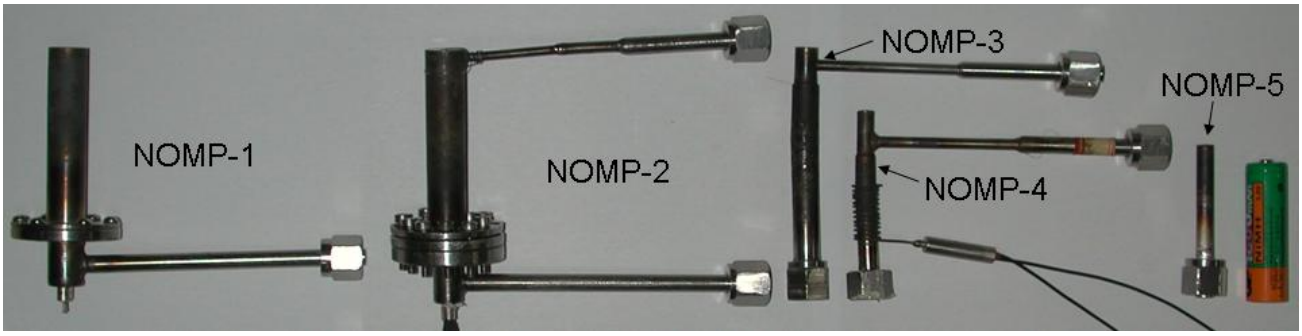

Figure 4. Nitrous Oxide Monopropellant Prototype (NOMP) designs.

Table 1. Main features of NOMP designs.

Parameter	NOMP-1	NOMP-2	NOMP-3	NOMP-4	NOMP-5
Diameter, mm	12	8	8	6	4
Volume, mm^3	4072	1659	1508	571	251
Mass flux, $kg/m^2/s$	0.09-0.71	0.46-2.08	0.37-1.39	1.43-3.34	2.66-2.88
Choked flow	No	Yes	Yes	Yes	Yes
Pressure range (gauge), bar	0	5-25	1-24	16-35	18-19
Mass, gm	81	151	37	37	21

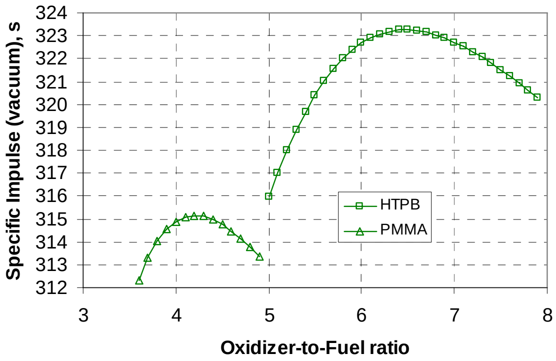

Figure 5. Theoretical specific impulse of nitrous oxide - solid fuel propellant combinations. (HTPB = hydroxyl-terminated polybutadiene; PMMA = polymethylmethacrylate)

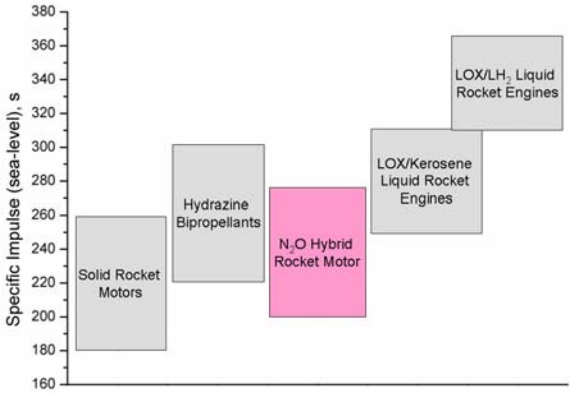

Figure 6. Performance comparison for selected booster propulsion. (LOX = liquid oxygen; LH_2 = liquid hydrogen; N_2O = nitrous oxide. Data taken from sources [5,6])

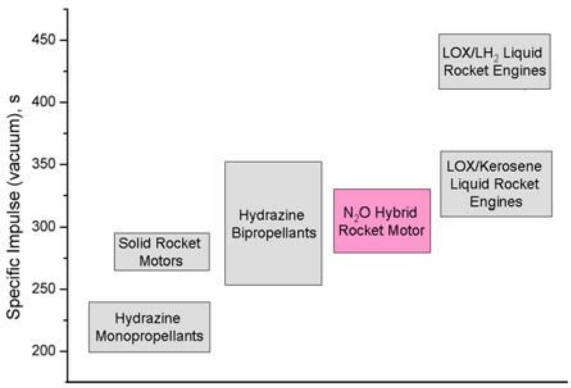

Figure 7. Performance comparison for selected upper-stage propulsion. (Data taken from sources [5,6])

For launcher applications specific impulse performance of N_2O-fed hybrids (Figure 6) is competitive to that of: presenting explosion hazard solid rocket motors; toxic hydrazine bipropellants; and cryogenic LOX/Kerosene rocket engines. For in-orbit applications specific impulse performance of N_2O-fed hybrids (Figure 7) is superior over hydrazine monopropellants, and is competitive to that of: presenting explosion hazard and single-shot, solid rocket motors; toxic hydrazine bipropellants; and cryogenic LOX/Kerosene rocket engines.

In the hybrid rocket motor under development at Tsinghua (Figure 8), N_2O decomposed in the catalyst pack to nitrogen and oxygen is injected into the combustion chamber igniting solid fuel upon contact. Then, combustion products expand through the nozzle producing thrust.

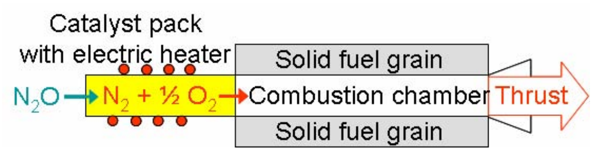

Figure 8. Schematics of N_2O-fed hybrid rocket motor.

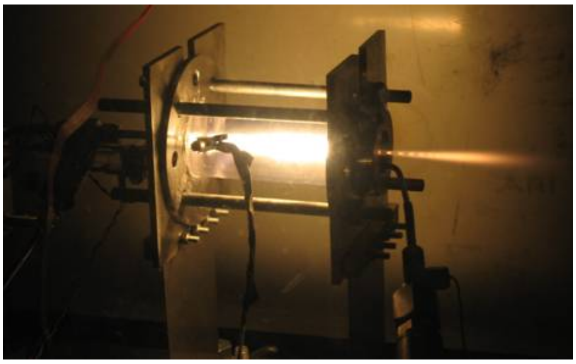

Figure 9. 4N-thrust N_2O/PMMA hybrid rocket motor firing on thrust stand.

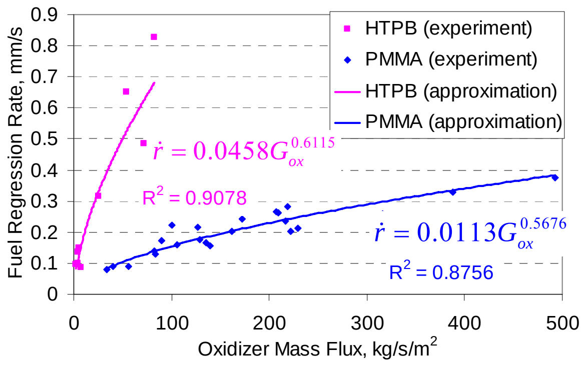

Figure 10. Solid fuel regression rates for N_2O-fed hybrid rocket motor. ($\dot{r}$ - fuel regression rate, mm/s; Gox – oxidizer mass flux, kg/s/m^2; R-squared value; The regression rates were obtained by weighing fuel grains before and after each firing.)

Performance of hydroxyl-terminated polybutadiene (HTPB or rubber) and polymethylmethacrylate (PMMA, acrylic, or plexiglas) solid fuels have been studied during test firings of lab-scale hybrid rocket motor (Figure 9). The empirical relationships for the solid fuel regression rates are shown in Figure 10.

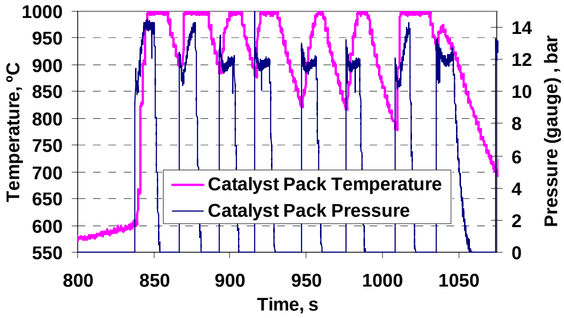

Figure 11. Restartable hybrid rocket motor test results. (Maximum temperature reading limit for K-type thermocouples was set to 1000ºC)

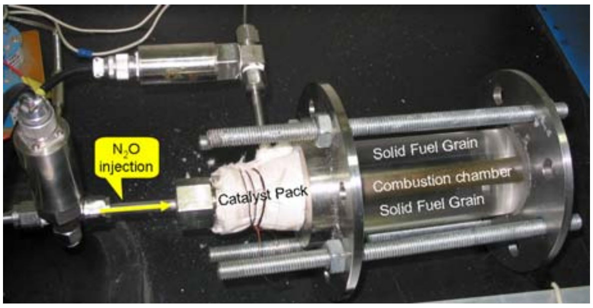

Figure 12. The restartable N_2O/PMMA hybrid rocket motor.

Figure 11 presents the results for the restartable N_2O/PMMA hybrid rocket motor (Figure 12) firing. In this test hybrid rocket motor was lit seven times. In the beginning of the 8th start (time=1040s) PMMA fuel grain burned through so that the firing was terminated. The measured motor ignition delay time for N_2O/PMMA hybrid rocket motor is ~0.2s.

Further investigation of the hybrid rocket motor is required to optimize its performance.

4. SUBSYSTEMS

Nitrous oxide self-pressurization feature eliminates the need in propellant expulsion subsystem making the propulsion system design simpler and lighter. This advantage, however, comes with the concern that excessive propellant chilling due to liquid-to-vapor phase change during propellant consumption out of the storage tank may cause undesired sharp vapor pressure drop resulting in the loss of liquefied gas self-pressurization feature leading to temporary liquefied gas propulsion system malfunction. Since propellant consumption (evaporation) is responsible for propellant chilling inside storage tank while heat transfer is responsible for its heating the problem occurs only when the first overtakes the second one, i.e. when propellant consumption rate out of the storage tank is excessive. Temporary propulsion system malfunction due to loss of liquefied gas self-pressurization feature can be avoided if propellant consumption rate does not exceed maximum limiting value specific for each propellant storage system design.

Experimental setup for studying of liquefied gas evaporation out of the tank is shown in Figure 13.

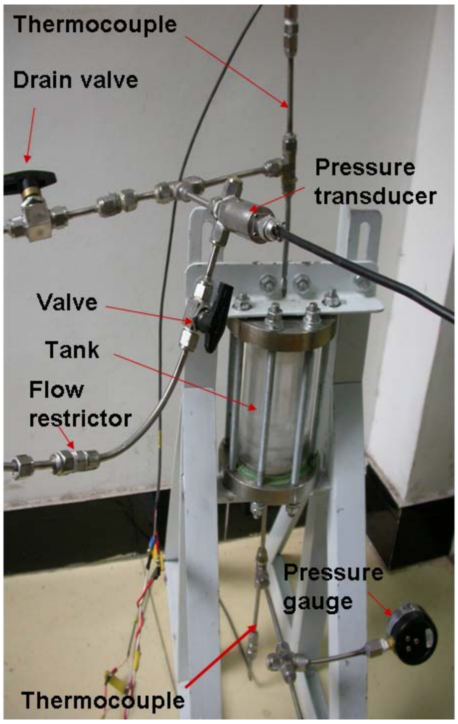

Figure 13. Experimental setup for liquefied gas testing.

One-dimensional, homogeneous model (Figure 14) developed and verified by experimental data can predict the maximum limiting value of propellant consumption to avoid the loss of liquefied gas self-pressurization feature. [7]

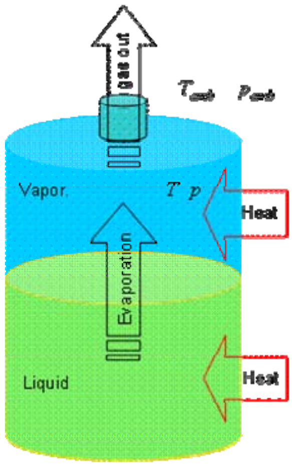

Figure 14. Sketch of storage tank self-pressurization by liquefied gas.

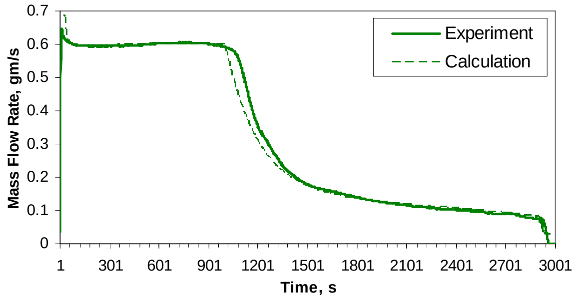

Figure 15. Results comparison for N_2O mass flow rate out of storage tank. (The initial mass flow rate curve step in the figure is because the flow out of tank was "controlled" by flow-meter heating the exhaust gas. When no liquid was left in the tank mass flow rate finally dropped to zero.)

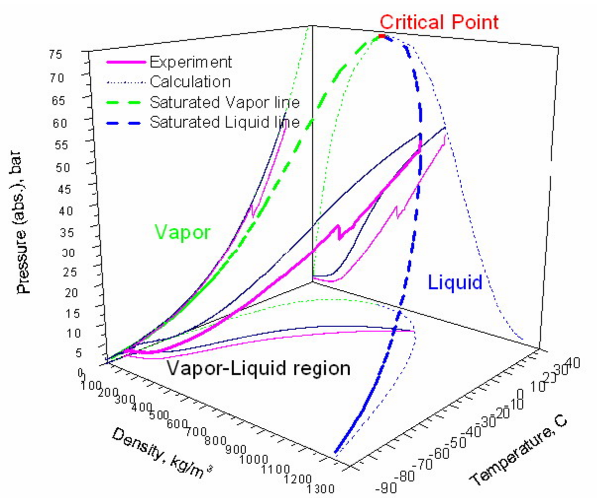

Figure 16. PDT-plot for nitrous oxide evaporation. (The initial pressure drop for experimental data is a dynamic pressure drop. The pressure spike for experimental data is due to heat of fusion passed to nitrous when the moisture condensed on the outside tank wall froze at 0°C.)

Satisfactory fit between empirical and theoretical results has been demonstrated for nitrous oxide evaporation out of the storage tank (Figure 15 and Figure 16).
The model will be further developed into 1-dimensional, heterogeneous, capable of handling binary mixtures, and boiling.

5. APPLICATIONS

While nitrous oxide monopropellant can be used for spacecraft station-keeping and small ΔV orbital maneuvering hybrid rocket motor can be applied for spacecraft large ΔV orbital maneuvering as well as launcher take off.

Liquefied gas self-pressurization model is useful for propellant storage and feed subsystems' operation prediction in-orbit. Since during take off gravity and inertia force liquid nitrous through the feed-lines, the model cannot be applied for launch at present. With little modification, however, the model will be capable of simulating launch case.
The analysis of nitrous oxide propulsion potential suggests that the most efficient application of this propellant is a multi-mode system in which different types of thrusters are fed from single storage tank. [8]
Figure 17 and Figure 18 give two possible examples of alternative nitrous oxide propulsion system options for a spacecraft. For the case of nitrous oxide propulsion the system is simpler. In addition, the system features higher flexibility to mission scenario change since nitrous oxide can be used till depletion by either thruster.

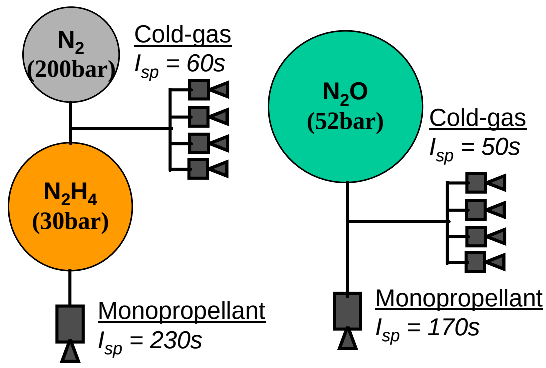

Figure 17. Schematics of Cold-Gas/Monopropellant propulsion system for a spacecraft.

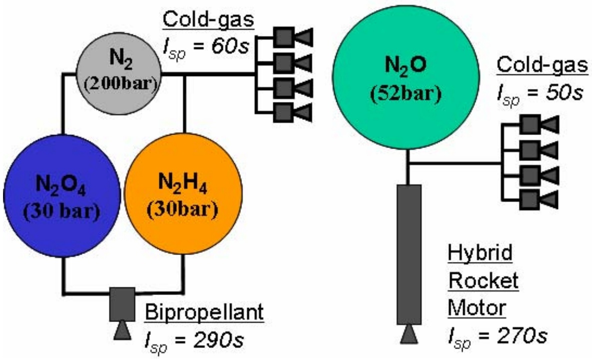

Figure 18. Schematics of Cold-Gas/Hybrid Rocket Motor propulsion system for a spacecraft.

Finally, nitrous oxide is non-toxic alternative to conventional hydrazine propulsion.

6. CONCLUSIONS

The several key-technologies currently under development at Tsinghua promote application of nitrous oxide propulsion.
For maximum performance benefit it is practical to combine different types of thrusters into multi-mode

propulsion system fed by nitrous oxide from single storage tank.

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